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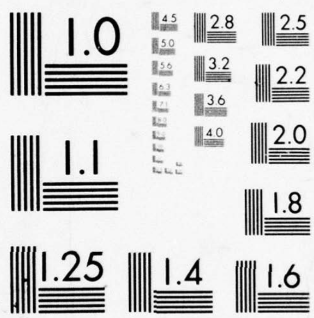

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RADC-TR-77-290, Part II (of two)
Final Technical Report
September 1977

INTRASYSTEM ELECTROMAGNETIC COMPATIBILITY ANALYSIS PROGRAM (IEMCAP) F-15 VALIDATION
Interpretation of the Integrated Margin

McDonnell Aircraft Company

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The validity and usefulness of the Intra-system Electromagnetic Compatibility Analysis Program (IEMCAP) is assessed, based on its predictions for the F-15 air superiority fighter aircraft. The aircraft was simulated using a combination of known, measured and approximated data. A sensitivity study is also performed, indicating the effects of approximating unknown IEMCAP input parameters. Finally, a physical interpretation of the integrated EMI margin is given, and an assessment is made of its validity as an EMC figure merit.

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The IEMCAP is shown to successfully predict the known overall compatibility of the F-15, and is also shown to predict interference between equipments in cases where receiver blanking is provided by the system. Cases in which the program incorrectly predicted interference are generally attributed to uncertainties in modeling non-required spectra rather than program inaccuracy.

The results support a judgment that the integrated EMI margin is a valid figure of merit for most equipment used on aircraft systems, with the exception of threshold vulnerable devices.

This report is divided into Part I and Part II. The first part of the report describes how the F-15 aircraft was used as data base for a shakedown of the IEMCAP code and an assessment of its predictions. The results of an input parameter is devoted to a detailed exposition on the meaning and physical significance of the integrated EMI margin, the quantity calculated by the IEMCAP as a measure of interference.

PREFACE

This report documents work conducted by McDonnell Aircraft Company, St. Louis, Missouri, on the Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP) F-15 validation effort, sponsored by Rome Air Development Center, Griffiss Air Force Base, New York, under Contract F30602-76-C-0193 from 8 April 1976 to 8 April 1977. Dr. Ronald A. Pearlman was the MCAIR principal investigator and Mr. Daniel J. Kenneally (RBCT) was the RADC Project Engineer.

This report is divided into Part I and Part II. The first part of the report describes how the F-15 aircraft was used as a data base for a shake-down of the IEMCAP code and an assessment of its predictions. The results of an input parameter sensitivity study are also presented. The second part of the report is devoted to a detailed exposition on the meaning and physical significance of the integrated EMI margin, the quantity calculated by the IEMCAP as a measure of interference.

Contributions to this contract effort from Dr. J.L. Bogdanor, Mr. G. Koester, Mr. R.E. Plummer and Mr. G.L. Weinstock are gratefully acknowledged. The timely and helpful suggestions of Dr. D. Weiner of Syracuse University are also acknowledged.

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1. INTRODUCTION

The Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP) computes an "integrated EMI margin" that is used in assessing Electromagnetic Compatibility (EMC) of elements of electronic systems.* The purpose of this part of the report is to treat this subject of integrated EMI margin (I.M.) in considerable depth, describing what it is, its physical meaning in relation to real hardware, how it is derived and computed in the IEMCAP and how it is used by the EMC engineer. Additional topics addressed include recommendation of a method for quantifying key parameters entering into the I.M. computation, description of an experimental procedure for correlating the I.M. calculation with test data and a general discussion of I.M. usefulness and limitations as an EMC figure-of-merit for elements of systems analyzed by the IEMCAP.

The IEMCAP system model assumes that the performance of all receptors in a system can be characterized in terms of average power and, accordingly, simulates these using a routine that integrates the interference power spectral densities present at the receptor input ports for assessment of EMI conditions. This assumption is examined and examples are presented indicating that the assumption is valid, at least for avionic systems using current technology. Exceptions are also noted and recommendations are made for alternative numerical analysis approaches for handling these.

The general IEMCAP system model is reviewed showing how the I.M. is derived along with the computational approach, with associated approximations, as implemented in the IEMCAP. Comments are made about the possible errors, including estimates of their magnitudes, resulting from these code approximations.

The IEMCAP system mathematical model employs certain parameters that require careful definition and that are deserving of further delineation of their foundation in real hardware performance characteristics. These receptor performance characteristics are examined in considerable detail and recommendations are made for an approach to quantifying the key parameters so that the IEMCAP predictions, including the I.M., have all of the system design considerations realistically factored into them.

A method is described for correlating the theoretically derived I.M. results with test data obtained from a laboratory experiment. Such an experiment, whose hardware parameters can be modeled in the IEMCAP, is expected to lend further credibility to the assumptions inherent in the IEMCAP system model and to the importance of the I.M. as a measure of EMI in system elements.

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*Appendix A, An Introduction to the IEMCAP, gives an overview of the IEMCAP program and of its basic approach to EMC analysis.

A general discussion is included of the reliability of the I.M. as the measure of EMI. This discussion considers the relative maturity of the system design and the associated levels of confidence in the parameters that are input to the IEMCAP. The general conclusion is that the I.M. becomes a better indicator of the EMC status of a system the closer the system approaches maturity, with all its parameters established and documented.

2. REVIEW OF THE IEMCAP SYSTEM MODEL

The discussion in this section is a review of the system model employed in the IEMCAP. The model brings together all of the emitter, receptor and transfer models within the IEMCAP into a linear system formulation for EMI predictions.

The system approach of the IEMCAP involves identifying all ports in the system having potential for signal coupling. These ports are categorized as emitters and receptors with associated signal coupling paths. Since the function of the IEMCAP is to determine, by analysis, whether signals from one or more emitters unintentionally coupling to a receptor will impair the receptor's required operation, it is necessary for the system model to include some characterization of the receptor's performance degradation due to interference signals. The IEMCAP assumes that average power of signals is the criterion appropriate for assessment of an interference condition in receptors. The rationale for this choice and an examination of its validity in relation to real hardware performance are discussed in Section 3.

The assumption in the IEMCAP system model that receptors are power vulnerable devices infers that their performance can be characterized in terms of average power of signals present at their input. The result of integration of signal power spectral densities is some power level at the receptor's detector which may or may not exceed a threshold power level defined for that receptor. This total power level at a receptor's detector will, in general, be a composite of desired signal power, thermal noise power and system induced interference power.

In order to simulate the physical operation of actual power vulnerable receptors the IEMCAP includes a routine for mathematically integrating the interference power spectral density present at a receptor's input, weighted by the receptor power transfer function, in its assessment of the interference power level at the receptor's detector. The model forms the ratio of this computed interference power level with the tolerable interference power level assigned to the receptor. This interference power ratio is called the "integrated EMI margin" (I.M.). When expressed in decibels, a positive I.M. is considered an interference condition while a negative I.M. is generally considered a compatible condition.

2.1 Bandwidth Role in Resolution of Signal Spectra. Before proceeding with a review of the mathematical relationships involved in the IEMCAP system model it is considered useful to make some observations regarding the manner in which information about signal power spectra becomes known. It is reasonable to assert that everything known about actual signal spectra is dependent upon instrument measurements. Thus, when knowledge is desired about the interference power present at a receptor's input, for example, this information is obtained by placing a power measuring instrument at that point to intercept the incident signals. Such a "power meter" may be viewed as an integrating device whereby it integrates the interference power spectral density of the signal over some frequency range. Usually it is desired to obtain some degree of frequency resolution in this power measurement so the integration range of the power meter is typically constrained by introducing frequency filtering into the signal path. The result of this filtering is that the meter's reading is effectively the result of integration of the signal power spectral density over the bandwidth of its bandpass filter. A number of such measurements with the filter retuned at each of several discrete frequencies enables a fine-grain mapping of the signal power spectra as a sequence of piecewise constant power levels versus frequency.

In the simple power spectra measurement procedure just described it will be clear that nothing more is known about the signal other than the fact that it produced a power level at the meter indicator for each bandwidth. To further characterize the signal at each point into narrowband and broadband classifications it is standard practice to vary the tuned frequency of the meter filter and to observe the effect of this retuning of the filter on the indicated power level. If such retuning of the filter produces a pronounced change in the meter reading the signal is classified as narrowband. If, on the other hand, the meter reading varies only moderately with filter retuning, the signal is classified as broadband.

The purpose of the preceding elementary discussion on measurement of signal power spectra is to emphasize the role of the measuring instrument bandwidth in the process of quantifying and classifying signal spectra. It will be seen in the following that the bandwidth also provides the key to successful mathematical treatment of emitter and receptor spectra in the IEMCAP system model.

2.2 The IEMCAP System Mathematical Model. Figure 1 depicts a hypothetical system situation in which a receptor (with index i) has unintentional coupling paths from several emitters. The coupling path from emitter j is characterized by the power transfer function, $T_{ij}(f)$, and the signal emanating from emitter j has power spectral density, $\eta_j(f)$. The receptor is shown divided into a collection of linear front end stages with overall power transfer coefficient, $\beta_i(f)$, and a detector stage. The IEMCAP analysis evaluates the signal coupling from the emitter output, through the transfer medium and through the receptor front end stages to the detector input. Any non-linearities in the receptor are assumed to reside in the detector and are not explicitly treated in the IEMCAP.

The linear communication theory relation assumed in the IEMCAP for the power at the input to the detector of receptor i due to emitter j is given by the following:

$$P_{Dij} = \int_{f_a}^{f_b} \eta_j(f)\, T_{ij}(f)\, \beta_i(f)\, df \qquad (1)$$

where P_{Dij} = Total power (in watts) received by receptor i (at its detector) from emitter j in the frequency range from f_a to f_b.

f_a = lowest frequency of interest

f_b = highest frequency of interest

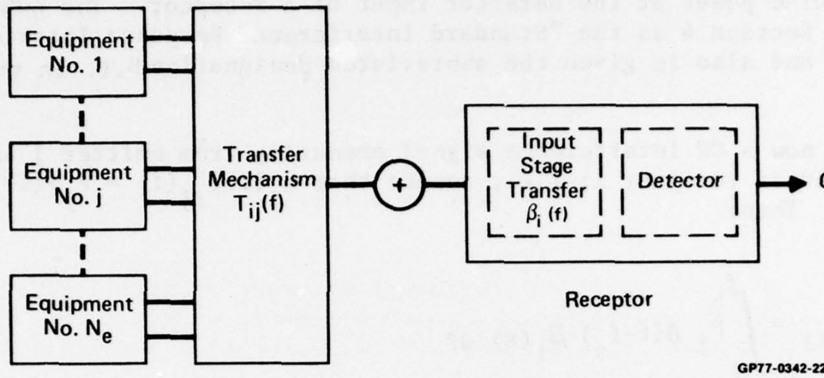


Figure 1. System Model Showing Emitter Ports, Transfer Mechanisms and Receptor Ports

The total received power at the receptor's detector due to all emitters coupling to receptor i is expressed as a summation as follows:

$$P_{Di}\Big]_{f_a}^{f_b} = \sum_{j=1}^{Ne} \int_{f_a}^{f_b} \eta_j(f)\, T_{ij}(f)\, \beta_i(f)\, df \qquad (2)$$

where P_{Di} = total power in watts received by receptor i at its detector input from all coupled emitters in the frequency range from f_a to f_b.

N_e = total number of emitters coupling to receptor i.

As mentioned previously, there is assumed to exist for every receptor a tolerable or threshold level of power at its detector due to interference signals that, if not exceeded, will permit acceptable required operation of the receptor. Let this interference threshold power level for receptor i in the present development be denoted K_{si}, a fixed power level in watts (i.e., frequency independent). Then, the ratio of the power calculated by equation (2) to this threshold power is defined to be an "EMI margin"; i.e., it is a measure of the actual interference power (evaluated in the frequency range from f_a to f_b) coupled to the detector of receptor i compared to that receptor's interference threshold power. If this ratio is greater than unity, an interference condition exists. If the ratio is less than unity, the system elements being evaluated are said to be compatible in the frequency range of equation (2).

The quantity K_{si} identified above as the interference threshold power for receptor i is discussed and defined in more detail in Section 4.2.4 of this part of the report where it is further related to the desired signal threshold power and thermal noise power at the detector input of a receptor. The quantity K_{si} is defined in Section 4 as the "Standard Interference Response Interference Power Level", and also is given the abbreviated designation S.T. in the following discussion.

Consider now a CW interference signal emanating from emitter j and centered in the passband of receptor i; i.e., assume that $\eta_j(f)T_{ij}(f) = \overline{P}_j \delta(f-f_o)$ in equation (1). Then:

$$P_{Dij} = \int_{f_a}^{f_b} \overline{P}_j \, \delta(f-f_o) \, \beta_i(f) \, df \tag{3}$$

$$= \overline{P}_j \, \beta_i(f_o)$$

where it is assumed that $f_a < f_o < f_b$, and

$\overline{P}_j$ = the CW signal level at the receptor input due to emitter j

$\beta_i(f_o)$ = the power transfer function of receptor i at its tuned frequency, f_o.

If the CW signal is increased to the level where the S.T. level at the detector, K_{si}, is just reached, the receptor input signal level is said to be at the "susceptibility" level, $S_i(f_o)$, at the receptor tuned frequency and the following relationship is obtained by substitution of these definitions into equation (3):

$$K_{si} = S_i(f_o)\beta_i(f_o) \tag{4}$$

If a CW signal is introduced at some other arbitrary frequency point, f_p, (where $f_a<f_p<f_b$), and the operations leading to equation (4) are repeated, there results a relationship, similar to equation (4), as follows:

$$K_{si} = S_i(f_p)\beta_i(f_p) \tag{5}$$

Now, since the frequency point, f_p, is arbitrary, it is reasonable to express equation (5) with the general frequency f, resulting in:

$$K_{si} = S_i(f)\beta_i(f) \tag{6}$$

Since the quantity, K_{si}, is identically the same constant power quantity in both equations (4) and (6), the following relationship is established by equating (4) and (6):

$$S_i(f) = S_i(f_o)\beta_i(f_o)/\beta_i(f) \tag{7}$$

that is, the susceptibility at any frequency is expressed in terms of the susceptibility at the tuned frequency and the receptor power transfer function. This susceptibility function of frequency is seen to be convenient in transforming EMI margin calculations to the input port of receptors, the point at which EMI assessments are made in actual practice for equipments.

The IEMCAP formulation enabling EMI assessment at the input port of receptors is developed by first substituting equation (7) into equation (1) with the following result:

$$P_{Dij} = \int_{f_a}^{f_b} \frac{\eta_j(f)\ T_{ij}(f)\ S_i(fo)\beta_i(fo)}{S_i(f)}\ df \tag{8}$$

Now, dividing both sides of equation (8) by the constant, $S_i(f_o)\beta_i(f_o) = K_{si}$, yields:

$$P_{Dij}\Big/K_{si} = \int_{f_a}^{f_b} \frac{\eta_j(f)\ T_{ij}(f)}{S_i(f)}\ df \tag{9}$$

The left side of equation (9) is the ratio of actual interference power at the detector to the S.T. and is the EMI margin evaluated in the frequency range from f_a to f_b as defined previously. The right hand side of equation (9) is the computation actually performed in the IEMCAP using quantities applicable at the receptor input port.

A result similar to equation (9) is easily demonstrated to hold for multiple emitters coupling to a receptor as expressed by equation (2). In this case the ratio of power at the detector to the S.T. takes the form:

$$P_{Dij}\Big/K_{si} = \int_{f_a}^{f_b} \sum_{j=1}^{Ne} \left[\frac{\eta_j(f)\ T_{ij}(f)}{S_i(f)}\right] df \tag{10}$$

An examination of the integrands of equations (9) and (10) will prove useful for later developments. The integrals themselves have been labeled as some kind of EMI margin applicable to the frequency range from f_a to f_b; important, useful EMI margins remain to be defined. Attention is directed to the dimensions of the quantities in the integrand of equation (9). The power spectral density, $\eta_j(f)$, has dimensions of watts/Hz; the power transfer function, $T_{ij}(f)$, is dimensionless and the susceptibility function, $S_i(f)$, has dimensions of watts. Hence, the complete integrand has the dimensions of watts/Hz/watts = 1/Hz and, since it is used in the calculation of EMI margins, has been designated as a "margin density" function. Thus, the integral, with respect to frequency, of a margin density function of frequency is a "margin".

2.3 <u>Point EMI Margins</u>. The foundation has been laid by the preceding discussion on which to build the mathematical relations for the EMI margins actually calculated by the IEMCAP for use in assessing the EMC status of systems. The first type of EMI margin calculated is called a "Point Margin" (P.M.). Its name derives from the fact that it is applicable in the neighborhood of a single frequency point. Both narrowband and broadband P.M.'s are calculated in the IEMCAP.

The mathematical development starts with reference to equation (9), the situation for a single emitter coupling to a receptor. In equation (9) the emitter power spectral density should first be considered as resolved into narrowband and broadband components; then a relation of the form of equation (9) will apply to each component taken separately. Next, the frequency range of integration is specialized so that it extends only over one "bandwidth factor" (BW), as defined in Table 1. Then, equation (9) is written as follows:

$$\text{P.M.} = \int^{BW} \left[\frac{\eta_j(f)\ T_{ij}(f)}{S_i(f)}\right] df$$

$$= \left[\frac{\eta_j(f_p)\ T_{ij}(f_p)}{S_{i(f_p)}}\right] (BW) \tag{11}$$

The interpretation of equation (11) is that the integrand of the integral is a piecewise constant margin density at any given frequency point, f_p, which, when multiplied by the bandwidth, BW, gives the P.M. at that frequency point. This is completely in accord with the ideas expressed previously about the information known about spectra (both emission and susceptibility spectra) being limited to the bandwidth of the instrument used in measurements. For the narrowband component of the emitter power spectral density, $\eta_j^N(f_p)$, equation (11) gives the narrowband P.M., or N.P.M. For the broadband component, $\eta_j^B(f_p)$, the calculation of equation (11) gives the broadband P.M., or B.P.M.

In the SGR portion of IEMCAP the N.P.M. and B.P.M. are calculated separately for each emitter coupling to a receptor and, where incompatibilities are found (B.P.M. or N.P.M. greater than unity) the emitter unrequired spectrum is adjusted to achieve compatibility, if possible. When all emitters coupling to the receptor have been so examined and adjusted where needed and where possible the IEMCAP then recomputes and prints out the adjusted N.P.M.'s and B.P.M.'s for each emitter along with actual adjusted emission limit levels at each frequency for possible use in preparation of narrowband and broadband limit specifications for each emitter. The meaning here of the word "possible" will become clear following development of the "integrated margin" to be discussed later.

After all emitters coupling to a receptor have been adjusted in SGR the program then computes a quantity called "total receiver power" at the receptor at each receptor frequency point using either actual known values at these points or else using "maximum values" obtained by interpolation when the receptor frequency falls between pairs of emitter frequencies (for more specific details on these procedures Reference 1 should be consulted). In computing "total received power" both the narrowband and broadband components are combined into a single total power quantity at each receptor frequency and this is considered to be the power present in the bandwidth applicable to each frequency point. Then a "total power point margin" (T.P.M.) is

Table 1. Bandwidth Factor

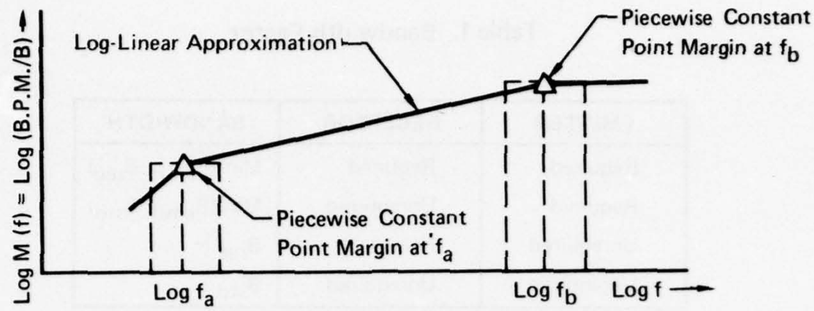
EMITTER	RECEPTOR	BANDWIDTH
Required	Required	Min (B_{emit}, B_{rec})
Required	Unrequired	Min (B_{emit}, B_{std})
Unrequired	Required	B_{rec}
Unrequired	Unrequired	B_{std}

B_{std} =	30% f_o	30 Hz $< f_o \leq$ 50 KHz
	10% f_o	50 KHz $< f_o \leq$ 1 MHz
	7% f_o	1 MHz $< f_o \leq$ 10 MHz
	5% f_o	10 MHz $< f_o \leq$ 100 MHz
	2.5% f_o	100 MHz $< f_o \leq$ 1 GHz
	1% f_o	1 GHz $< f_o \leq$ 18 GHz

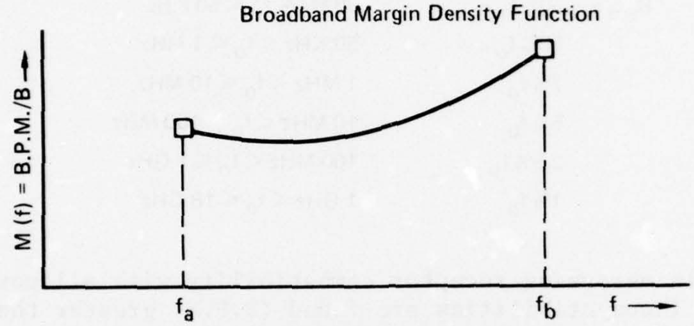
computed for use in assessing receptor compatibility with all coupled emitters adjusted. If now incompatibilities are found (T.P.M. greater than unity at one or more receptor frequencies), the receptor nonrequired spectrum is adjusted until compatibility is achieved, if possible. After receptor adjustment where needed and where possible the IEMCAP then recomputes and prints out the T.P.M. along with the adjusted receptor susceptibility levels at each frequency for possible use in preparation of a susceptibility specification for the receptor.

2.4 Integrated EMI Margins. The point EMI margins (P.M.'s) discussed in the preceding paragraphs were seen to be computed at several discrete frequencies in a frequency range that is common to each emitter and a receptor. These point margins are used in the program to compute still another type of EMI margin which is called the "integrated EMI margin", or simply I.M. This I.M. is used as the measure of overall EMC for a receptor in its emission environment. Four distinct forms of the I.M. are computed in the IEMCAP: a narrowband I.M. (N.I.M.), a broadband I.M. (B.I.M.), their sum (I.M.), and a total I.M. (T.I.M.). The integrated margins have usefulness in judging the EMC performance and cost effectiveness associated with the spectrum adjustments carried out in the SGR. The general approach used in the IEMCAP in the calculation of these I.M.'s is presented in the following.

Broadband Integrated Margin. The broadband I.M. calculation is developed first. The solution sought is represented by equation (9) where the limits of integration are now the lowest frequency and the highest frequency common to the emitter-receptor pair. The development is aided by reference to the graphical presentation of Figure 2 in which are shown plotted the broadband point margins (B.P.M.'s) at two successive frequencies in the required range. The B.P.M.'s are plotted in decibels versus the logarithm of frequency so that the presentation is in log-log coordinates. This is of some importance since the IEMCAP maintains records of margins in decibels and of frequencies on a logarithmic basis, making appropriate conversions when actual values



a) Log-Linear Approximation of Broadband Margin Density Function



b) Broadband Margin Density Function Derived from Log-Linear Function

Figure 2. Broadband Integrated Margin Approach

are needed for computations. Shown by phantom lines in Figure 2 are the bandwidths associated with the two frequency points and the piecewise constant B.P.M. values applicable in these bandwidths. The situation shown has the frequencies separated such that the bandwidths do not overlap. Other situations could exist elsewhere for this hypothetical emitter-receptor pair in which frequencies could be so close that the associated bandwidths do overlap. Consequently, it would not do to simply approximate the integration by a summation of the rectangular areas since this would probably result in errors including both omitted frequency regions (the case shown in Figure 2) and overlapping frequency regions. A different approach to integration is therefore indicated.

The integration approach for B.I.M. used in the IEMCAP involves first converting the point margins at each of the two frequencies in Figure 2 to piecewise constant logarithmic margin densities by subtracting the logarithm of the bandwidth at each frequency point from each margin expressed in decibels. Then these discrete logarithmic margin densities are connected by a straight line in the log-log coordinates. The resulting log-log function is transformed to an actual margin density function and an analytical integration, described by equation (9), is performed in closed form for each interval between successive frequencies. The complete B.I.M. is then obtained by summing all of the incremental B.I.M.'s computed for each intermediate and contiguous interval, over the entire frequency range.

The mathematical relations involved in the B.I.M. calculation are expressed as follows:

$$\text{B.I.M.} = \sum_{r=1}^{Nc} m_{rB} \tag{12}$$

where N_c = the combined total of all emitter and receptor frequencies over the entire common frequency range

m_{rB} = the incremental B.I.M. obtained from integrating between frequencies f_r and f_{r+1}.

Now, to obtain the incremental B.I.M. (m_{rB}) in the frequency interval from f_r to f_{r+1}, the following relationships are established from the straight line graphical presentation given in Figure 2.

The equation of the straight line margin density function in log-log coordinates is:

$$10 \log_{10} M - 10 \log_1 M_r = \left[\frac{10 \log_{10} M_{r+1} - 10 \log_{10} M_r}{10 \log_{10} f_{r+1} - 10 \log_{10} f_r}\right]\left[\log_{10} f - \log_{10} f_r\right]$$

or

$$\log_{10}\left[\frac{M}{M_r}\right] = \left\{\log_{10}\left[\frac{M_{r+1}}{M_r}\right] \Big/ \log_{10}\left[\frac{f_{r+1}}{f_r}\right]\right\} \log_{10}\left[\frac{f}{f_r}\right]$$

Now, let

$$a = \log_{10}\left[\frac{M_{r+1}}{M_r}\right] \Big/ \log_{10}\left[\frac{f_{r+1}}{f_r}\right] \tag{13}$$

Then $\log_{10}\left[\frac{M}{M_r}\right] = \log_{10}\left[\frac{f}{f_r}\right]^a$, or $M = M_r\left[\frac{f}{f_r}\right]^a$

And

$$m_{rB} = \int_{f_r}^{f_{r+1}} M(f)df = \int_{f_r}^{f_{r+1}} M_r\left[\frac{f}{f_r}\right]^a df = \frac{M_r}{(a+1)}\left[\frac{f_{r+1}^{a+1}}{f_r^a} - f_r\right]^* \tag{14}$$

* See Reference 1 for the case where a = -1

Narrowband Integrated Margin. Calculation of the narrowband integrated margin again involves the use of a margin density function that is derived from the narrowband point margins previously calculated at discrete frequencies in the IEMCAP. In this case the margin density function is formed by straight line connection of the narrowband point margins in the actual margin-frequency coordinate system as illustrated in Figure 3. The program assumes that the bandwidth factor is constant over the interval between two successive frequency points involved in the narrowband integrated margin calculation. Thus, the point margins at the discrete end frequencies are converted to piecewise constant margin densities by dividing them by the bandwidth factor associated

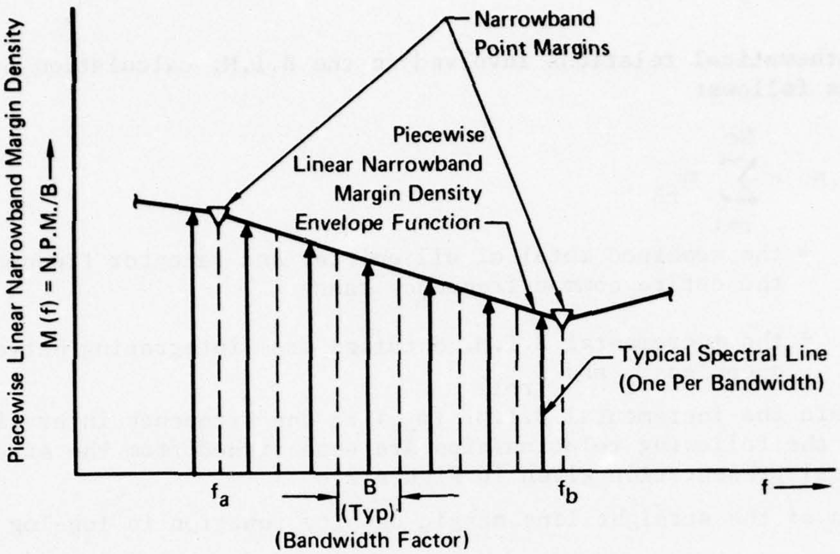


Figure 3. Narrowband Integrated Margin Approach

with the highest frequency in the interval. Then these piecewise constant margin densities are connected by a straight line to form a margin density function in the frequency domain (Figure 3), and the incremental narrowband integrated margin, m_{rN}, is calculated, using the formalism of equation (9), as the area under the curve in Figure 3. The complete N.I.M. is then obtained by summing all of the incremental N.I.M's computed for each intermediate and contiguous interval over the entire frequency range.

With the assumptions just stated the narrowband integrated margin is written as follows:

$$\text{N.I.M} = \sum_{r=1}^{Nc} m_{rN} \tag{15}$$

where N_c = the combined total of all emitter and receptor frequencies in the common frequency range.

m_{rN} = the incremental N.I.M. obtained from integrating between frequencies f_r and f_{r+1}.

Each incremental N.I.M (m_{rN}) is given by:

$$m_{rN} = \int_{f_r}^{f_{r+1}} M(f)\, df \tag{16}$$

$$= \tfrac{1}{2} \left[M(f_{r+1}) + M(f_r) \right] \left[f_{r+1} - f_r \right]$$

Total Integrated Margin. The total integrated margin is computed as the composite of the broadband and narrowband integrated margins following emitter and receptor adjustments in SGR. This total integrated margin, T.I.M., is thus given by:

$$\text{T.I.M.} = \sum_{j=1}^{Ne} (\text{B.I.M.} + \text{N.I.M.}) \qquad (17)$$

2.5 Use of the Integrated and Point Margins. As discussed previously, following emitter and receptor unrequired spectrum adjustments in the SGR, the IEMCAP computes and prints out updated values of narrowband and broadband point margins (N.P.M. and B.P.M.) at emitter frequencies for each emitter and also computes and prints out an updated total point margin (T.P.M.) at each receptor frequency. Adjusted narrowband and broadband emission limit levels for emitters and adjusted receptor susceptibility levels are also available in the printout as the initial step in the iterative process leading to the establishment of equipment specifications.

The program also computes and prints out two forms of integrated margin, reflecting all spectrum adjustements. The integrated margin (I.M.) is printed for each emitter coupling to a receptor and this is employed by the user to judge the overall effectiveness of the spectrum adjustments performed by the program so far as individual emitters are concerned. The total integrated margin (T.I.M.) is similarly used to assess overall compatibility of the receptor, with all coupled emitters considered, after the program adjustments.

Integrated margins greater than unity (positive in decibels) indicate that EMI conditions persist even after adjustments have been made of the various unrequired spectra. Under such conditions the recommended procedure is to carefully review all of the associated point margins (P.M.'s) to isolate the cause(s) of the problem(s). The P.M.'s will enable determination whether the EMI is the result of one or more of the following four conditions:

a) required emissions to required receptor spectra;
b) required emissions to unrequired receptor spectra;
c) unrequired emissions to required receptor spectra;
d) unrequired emissions to unrequired receptor spectra.

In case (a) the EMI is unavoidable and will have to be dealt with by special measures such as receiver blanking. In case (b) the receptor unrequired spectra were not adjusted sufficiently to eliminate EMI in the region of required emissions. If the receptor adjustment is already at the practical limit in these regions, the EMI will have to be fixed by use of system EMI control measures such as filtering, shielding, rerouting wires, etc. Case (c) indicates that the adjustment of one or more emitters was insufficient in the receptor required range and the particular offender(s) can be identified by review of the N.P.M.'s and B.P.M.'s for the emitters in the vicinity of the receptor required spectrum. Such a condition will either necessitate further emitter adjustments, if feasible, or else will require use of system EMI control techniques. Case (d) will result if one or more emitters or the receptor have received insufficient adjustment and a scanning of the various P.M.'s should reveal the cause(s) of the problem. Fixing case (d) could entail further adjustment of certain emitter spectra or the receptor spectra, if practical, or else application of EMI control methods.

In all of the cases discussed above the integrated margins provide the evidence that incompatibilities existed at the completion of an SGR run while the point margins provided the clues for pinpointing the causes of the problems. The objective of applying fixes to the problem areas is to drive the integrated margins toward moderately negative values in decibels in a subsequent exercise of the program. When this result is achieved for each receptor in the system (except for unavoidable EMI situations) compatibility of the system is assured. There is always the possibility of coarse, of over-specifying the system EMC requirements, in which event the system EMC design may not be cost effective. The integrated margins also convey information about this condition when their values in decibels are strongly negative. This could mean that unduly stringent adjustments have been applied to spectra in the SGR and the user will then want to relax the input criteria so that the integrated margins, in a subsequent IEMCAP run, will reduce to moderately negative values in decibels.

When the integrated margins all indicate compatibility, if possible, and do not have excessively large negative decibel values, the spectral levels printed by the IEMCAP are probably then suitable for use in preparing equipment specifications.

2.6 IEMCAP Treatment of Broadband Emission Spectra. A further aspect of the IEMCAP system model that needs discussion is the manner in which broadband emission spectra are treated in the program. The integrated EMI margin is evaluated by a weighted integral of an emitter's power spectral density in watts per hertz received at the input port of a receptor. Broadband emission limits, however, are not specified in terms of power spectral density but in terms of the quantity measured by a standard EMI test receiver, such as an Empire Devices NF-105; namely, the current spectral level in microamps per megahertz. The current spectral level is a measure of the peak current contained in the instrument bandwidth.

Required spectra of emitters and receptors use either the mathematical models coded into the program or user specified data. For a given emitter with a known modulation waveform, a mathematical relationship between the average power in a frequency interval and the peak current in the interval is used by the program to convert the power spectral density calculated by one of the spectrum models to an equivalent current spectral level in specifying the broadband emission level. This quantity is ultimately converted back to the original value of power spectral density in order to calculate the integrated margin on the basis of average power.

For emitters where the user specifies the required emission level, the broadband emission level is already presented in terms of a current or voltage spectral level. The non-required emission spectra of all emitters, moreover, are represented by military specification (mil-Spec) limit levels on spectra. Both MIL-STD-461 and MIL-I-6181 are coded and made available for user choice between them depending upon the equipment being modeled. These levels are also presented in terms of current or voltage spectral level, as measured by a standard EMI test receiver. In order to evaluate these emissions from a viewpoint of average power, the IEMCAP assumes the signals can be modeled as broadband Gaussian noise.

3. VULNERABILITY OF RECEPTORS

This section examines the IEMCAP treatment of the important issue of the reaction of the receptors to interference signals. It is found that receptors can be categorized in two basic classifications: a) those whose performance can be characterized in terms of average power and b) those whose performance can be characterized in terms of an amplitude threshold.

The following paragraphs discuss the results of an investigation of the receptor responses of a variety of equipments found in weapons systems. The findings are examined in relation to the assumptions in the IEMCAP and recommendations are made for alternate approaches that the IEMCAP could employ to model device responses not presently treated in the program.

3.1 Assumptions in the IEMCAP. As discussed in Section 2, the IEMCAP system model contains the assumption that the receptors in a system can be characterized in terms of average power and consequently the power spectral density of signals is integrated across the entire spectrum in order to obtain the average power at their inputs. The program accordingly includes provisions in its system mathematical model for simulating this power integration. The IEMCAP model is structured to integrate the power of unintentional signals coupled to all receptors and compares the accumulated interference power in each instance with a susceptibility power level defined for each receptor by means of a quantity called the integrated EMI margin.

It is instructive to examine the rationale for the choice of signal average power as the criterion used in the IEMCAP for characterization of receptor performance. Following is a list of the key factors favoring that choice:

a) The performance of receptors in communications systems is invariably a function of average signal power (this includes voice communications, digital data, radar, navigation, electronic warfare, etc.).
b) The performance of receptors of analog signals is generally sensitive to average power.
c) The performance of receptors of digital logic signals may have a characterization in terms of average power.
d) Since multiple sources of signals tend to be uncorrelated, the average power of the sum is simply the sum of the average powers.
e) Unrequired spectra, even for single emitters, will probably most often tend to have random phase relationships in the time domain; therefore average power is a convenient representation.
f) State-of-the-art emission and coupling models incorporated in the IEMCAP are modeled in the frequency domain, and accordingly, contain no phase information for analysis of coherent signal combining.

Several of the factors listed (items a, b, d, and e) provide definite motivation for the selection of average power as the basis for interference assessment in receptors. Item c, which comments on digital logic receptors, indicates an uncertainty about the power performance criterion of such devices and, as will become evident, is presently considered to be a weakness of the IEMCAP that should be strengthened. Item f is mentioned as a reminder that an attempt to assess interference on a coherent basis in the time domain would likely involve a significant model development effort.

Table 2 is a listing of important types of receptors found in systems, categorizing them according to their vulnerability to power or to a threshold voltage or current level. It is seen that analog devices dominate the extensive power - vulnerable list while digital logic devices which are coming into widespread use, are the principal threshold - vulnerable receptors.

3.2 F-15 Mini-System Receptor Characterization. The large mini-system assembled to simulate the F-15 weapon system for assessment of the IEMCAP EMI prediction capability consists of a total of 230 ports. Of these, 149 are receptor ports (several of these are also emitters) which were assessed to categorize them as either power - vulnerable or as threshold - vulnerable. The result of this assessment, whose basis is described in Part I of this report, is that over 90 percent of the mini-system receptors are judged to be vulnerable to average power. The performance of all of the antenna ports and most of the wire ports are categorized in terms of average power.

Since the criteria for selecting equipments in the F-15 mini-systems did not include power vulnerability, it is considered probable that the complete F-15 weapon system could be characterized as having a similar preponderance of power sensitive receptor devices. It is concluded, on the basis of this assessment that the IEMCAP assumption of power vulnerability of receptors is probably valid for most equipments of the type found in the F-15 aircraft. However, as was pointed out in the discussion in Part I, even though the threshold sensitive devices on the F-15 are relatively few in number, they may have serious interference problems that IEMCAP, as presently configured, would not successfully predict. A possible approach to overcoming this suspected deficiency of the IEMCAP is outlined in the following.

3.3 Recommendation for Treatment of Threshold Devices. An approach for analytically predicting the peak levels (peak current or peak power) emanating from emitters and comparing these to the peak response characteristics of threshold sensitive devices has been conceived for possible future implementation in the IEMCAP. An outline of this analytical approach is presented in Appendix B. It is seen that the analysis is cast in the same general framework as the average power analysis approach used presently in the IEMCAP so that no fundamental changes would be required in the IEMCAP system model to accommodate its implementation.

The general approach proposed for assessment of compatibility of threshold devices is now outlined, following the analysis procedure of Appendix B. The similarity between this proposed approach using peak currents and the present program approach using average power arises in the integration of spectral density. The approach involves defining a peak current susceptibility for the threshold - vulnerable device and then comparing the peak current level incident at the device input to this susceptibility level. The ratio of these two levels at discrete frequencies yields a "point current margin" (P.C.M.)

Table 2 Categorization of Receptors

Type of Receptor	Type of Waveforms Used	Vulnerability
1. RF Receiver	CW, Modulated RF, Pulsed RF	P
2. Traveling Wave Tube Amplifier	CW, Modulated RF, Pulsed RF	P
3. Analog Audio or Video Band Receptor	DC Analog, Audio Frequency Signal, Video	P
4. Speaker or Earphones	Audio	P
5. Diode Switch (Selecting 2 or more Devices)	Switched Discrete	P, T
6. DC - Coupled Input to Solid-State Logic Device[1]	Pulse Train, Discrete	P, T
7. AC/DC Input to Voltage Regulator or Power Bus	AC/DC Power	P
8. Synchro Control Transformer	Three-Wire Synchro Signal	P
9. Motor	AC/DC Power	P
10. Meter Movement	DC Analog, Audio Frequency Analog	P
11. Relay Coil	Switched Discrete, AC/DC Power	P
12. Lamp Bulb, Tube Filament	Switched Discrete, AC/DC Power	P
13. Light Emitting Diode	Switched Discrete, AC/DC Power	P, T
14. Electro-explosive Device	DC Power	P

[1]Single input or differential comparator, either transistor or integrated circuit, e.g., Complementary MOS (CMOS), Diode Transistor Logic (DTL), Transistor-Transistor Logic (TTL), Low Power Schottky (LS) or Emitter-Coupled Logic (ECL).

P = Average Power
T = Threshold

as a measure of compatibility at each frequency point. Additionally, a "peak current margin density" function is found using the ratio of the "current spectral level" to a "current susceptibility function." This current margin density function is then integrated over a frequency range of interest to yield an "integrated current margin" (I.C.M.) based on peak current ratios. Inherent in this approach to calculating an I.C.M. is the fact that all of the peak current contributions to the integral combine in phase. Appendix B develops **methods** for calculating the P.C.M. and I.C.M. for both the single emitter case and also for multiple emitters, in which case the computation would yield a total P.C.M. and a total I.C.M.

It is believed that the peak current margins that would be computed, using something like the approach outlined in Appendix B, would make possible assessment of the affect of transients (which will generally contain very little power) on threshold - vulnerable devices. These effects would most likely be revealed in the I.C.M.'s and more detailed information would be provided by examination of the P.C.M.'s.

Since the earlier discussion made clear that equipments in weapons systems contain both power and threshold vulnerable receptors, implementation in the IEMCAP of an approach such as that described in Appendix B should be such as to make it an alternative to the average power analysis, not its replacement. The user could then call for computation of peak levels for those receptors he knows or suspects should receive this treatment. If he isn't sure, he could specify that both types of analysis be performed, thus deferring judgement about which prediction is applicable until more information is available.

4. RECEPTOR PERFORMANCE CHARACTERISTICS

The IEMCAP system model employs a number of parameters requiring careful definition and examination of their formulation in actual hardware performance characteristics. These receptor performance characteristics are examined in considerable detail and an approach is discussed for quantifying the key parameters so that the IEMCAP predictions, including the integrated EMI margin, have all of the system design considerations factored into them.

4.1 Definitions of Receptor Terminology. Following is a set of definitions of terms applied to parameters of power vulnerable receptors. These definitions are set forth here with the objective of clearly distinguishing several signal levels in receptors that are used in the IEMCAP so that its numerical EMI predictions reflect actual hardware performance behavior in the system environment. There are six such signal levels which are later used in describing actual receptor performance in terms of signal-to-noise and signal-to-interference power ratios.

4.1.1 Standard signal response. A standard signal response refers to some minimum acceptable behavior of an equipment in the absence of interference as determined from an "interference-free" performance curve. (A standard signal response could be signal-to-noise ratio, probability of error, mean square error, articulation score, etc.). This standard signal response can be related to a detector input signal-to-noise ratio, where the noise is due solely to that introduced in the front end.

4.1.2 Standard interference response. A standard interference response refers to some minimum acceptable behavior of an equipment in the presence of interference as determined from an "interference present" performance curve. (A standard interference response could be signal to interference ratio, probability of error, mean square error, articulation score, etc.). As in the case of standard signal response, these measures can be related to a detector input signal-to-interference power ratio. An independent parameter in the input signal-to-interference ratio is the noise introduced by the receiver front end. To properly illustrate the interference effects on equipment performance, performance curves can be developed relating signal-to-interference ratios for constant signal-to-noise ratio. It is noted that as the interference power level goes to zero, the equipment performance approaches that dictated for the interference free situation.

4.1.3 Minimum detectable signal. The minimum detectable signal refers to the desired signal at the receptor input terminals that produces a "standard signal response" of the equipment in the absence of interference. Thermal noise generated in the front end is assumed present.

4.1.4 Minimum acceptable signal. The minimum acceptable signal refers to the desired signal at the receptor input terminals that results in a "standard interference response signal power level" at the detector in the presence of interference. Thermal noise generated in the front end is assumed present.

4.1.5 Standard interference response interference power level. The standard interference response interference power level is the maximum average power of interferers at the detector input that enables a "standard interference response" for a "minimum acceptable signal". If the interference average power to the detector is greater than the "standard interference response interference power level", interference is said to exist.

4.1.6 Susceptibility power level. The susceptibility power level refers to the average power of an interference signal at the receptor input terminals that results in a "standard interference response interference power level" at the detector. This "Susceptibility Power level" is the level that should be assigned as the input parameter for all receptors in the IEMCAP instead of the "sensitivity level" identified in Reference 1.

4.2 Communications Theory Basis. The discussion in the following paragraphs will develop relationships among the signal power quantities defined in Section 4.1 in terms that are commonly encountered in communications theory and communications systems engineering. In the process of this development, a systematic basis is established for quantifying the "Susceptibility Power Level" on which the IEMCAP computations depend and, therefore, which affects the accuracy of the program's EMI predicitions.

4.2.1 Generalized receptor power response. With reference to the "input power response" function for a receptor given in Figure 4, consider the method employed to obtain the data used to plot such a characteristic.

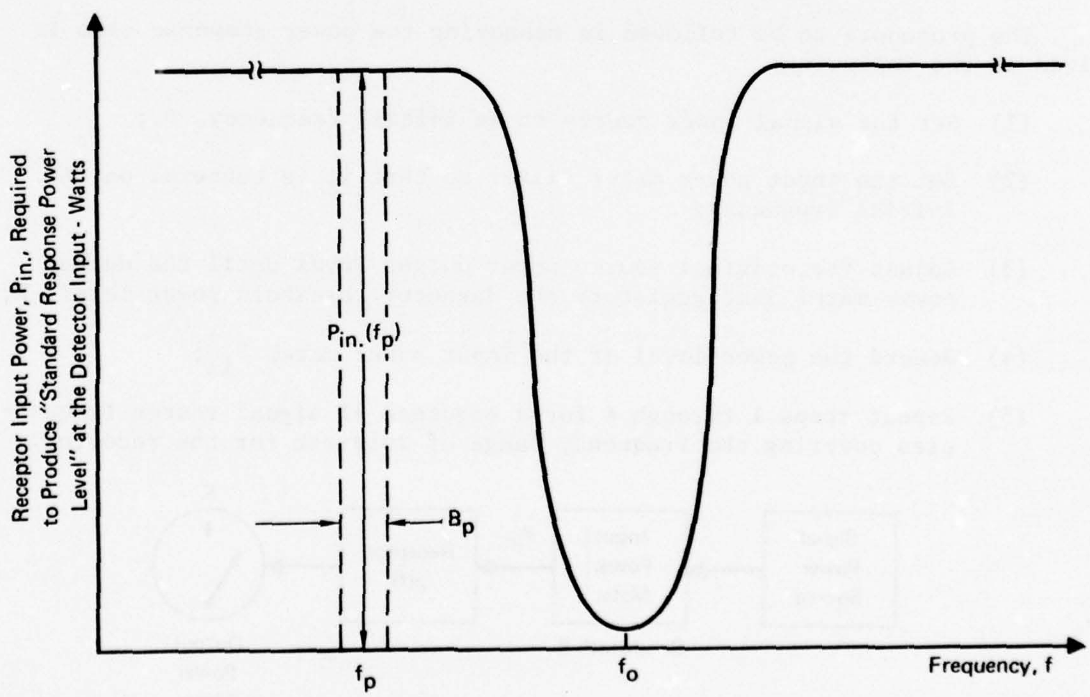


Figure 4. Generalized Receptor Input Power Response

First, a number of assumptions are stated about the receptor and about the measuring instruments used to obtain the response data:

(a) The receptor's performance can be related to the average powers present in the signal, noise and interference;

(b) The receptor has a linear power transfer characteristic, $\beta(f)$, which transforms power at its input to power at its detector;

(c) The receptor is characterized by a particular performance quality measure;

(d) There is an accepted standard method for determining when the receptor's detection power "threshold" has been reached; i.e., that detector signal power level, K, which just satisfies the aforementioned performance quality measure for the receptor;

(e) A calibrated average power measuring instrument of known bandwidth, B, is available for connection between a variable power level, variable frequency signal source, and the receptor input port;

(f) The input meter bandwidth, B, is narrow compared with both the source and receptor bandwidths. (The bandwitdh at frequency f_p is denoted B_p).

Figure 5, is a simplified block diagram of a possible receptor power response test setup.

The procedure to be followed in measuring the power response data is given in the following:

(1) Set the signal power source to an initial frequency, f_1;

(2) Set the input power meter filter so that it is centered on the initial frequency;

(3) Adjust the original source power output level until the output power meter just registers the detector threshold power level, K;

(4) Record the power level of the input power meter P_{in};

(5) Repeat steps 1 through 4 for a sequence of signal source frequencies covering the frequency range of interest for the receptor.

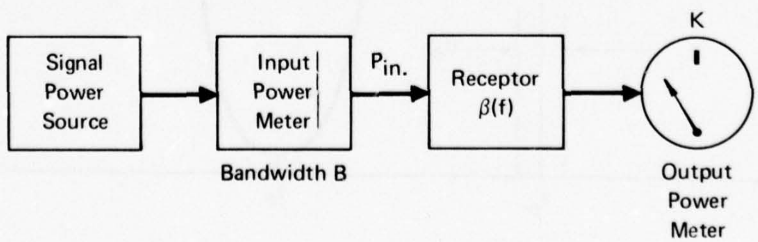


Figure 5. Receptor Power Response Measurement Setup

Consider now the mathematical basis for the power transfer through the receptor from its input to its output. Let $\eta(f)$ represent an input power spectral density (i.p.s.d.); then the output power spectral density (o.p.s.d.) is just

$$\text{o.p.s.d.} = \eta(f)\beta(f) \tag{1}$$

and the total power at the receptor's detector is the result of integrating (1) over all frequencies as follows:

$$P_{out} = \int_0^{\infty} \eta(f)\beta(f)df \tag{2}$$

Now, in using (2) to represent the power response measurement scheme for a receptor, recall that the input power meter was assumed to possess a filter characteristic with bandwidth, B_p, associated with a particular frequency setting, f_p, of the meter as illustrated in the graph of Figure 4. The practical effect of the meter filter is to constrain the integration range of Equation (2) to the instrument bandwidth at each frequency point. Consequently, both the measurement of input power and the measurement of output power are so constrained, such that the power levels obtained are mean values in the instrument bandwidth intervals. Accordingly, the input power meter measures a level of power incident from the signal source which is also representable as an integration over the meter bandwidth as follows:

$$P_{in}(f_p) = \int^{B_p} \eta(f)\beta_I(f)\, df = \overline{\eta(f_p)}B_p \tag{3}$$

where $\beta_I(f)$ is the meter filter power transfer characteristic which is assumed to be unity within the meter passband and $\overline{\eta(f_p)}$ is the mean value of $\eta(f)$ over the integration interval.

It is seen that Equation (2) should properly be written to include the input power meter power transfer characteristic, as well as the receptor power transfer characteristic; i.e., the following formalism is appropriate:

$$P_{out} = \int_0^{\infty} \eta(f)\beta_I(f)\beta(f)df \tag{4}$$

which reduces, under the previously stated instrument bandwidth constraint, to the following:

$$P_{out} = \int^{B_p} \eta(f)\beta(f)\beta(f)df = \overline{\eta(f_p)}B_p\beta(f_p) \tag{5}$$

or, using (3):

$$P_{out} = P_{in}(f_p) \quad \beta(f_p) \tag{6}$$

Equation (6) says that, within the bandwidth of the measuring instrument at the measurement frequency, the average power transferred from the receptor input to its detector is simply the product of the input power and the receptor power transfer function associated with the particular measurement frequency. This advantageous and realistic simplification of the integral of Equation (2) is routinely used in the IEMCAP broadband EMI point margin calculations.

According to the previously outlined test procedure, the input power level, $P_{in}(f_p)$, in (6) is to be set, such that the output power meter just registers the threshold power level, K. Hence, the following relationship is established:

$$K = P_{in}(f_p) \quad \beta(f_p) \tag{7}$$

Equation (7) says that, at every frequency point across a spectrum of interest for a receptor, there is a value of input power which just causes the output power level to be at some threshold level. This relationship holds whether the input power is narrowband, broadband, or a combination, and it is understood to be valid on a frequency point-by-frequency point basis under the assumption that it represents the input-to-output power transfer within an instrument bandwidth at each frequency point.

Examine now the question of the definition of the receptor output power threshold, K. There are three such power levels that will be discussed and these will be seen to be related to one another and to the measure of performance quality that is decided upon for the receptor. For each of the three output threshold power levels, there is a corresponding input power level defined by Equation (7) for each frequency point.

The first two output threshold power levels to be defined will refer to "desired signal" output power thresholds. The third threshold level will refer to an "interference signal" output power threshold.

4.2.2 Minimum detectable signal. A receptor operating in an interference-free environment is said to be characterized by some minimum level of input signal which just provides desired performance quality. This "minimum detectable signal" at the receptor input port competes only with thermal noise power generated internally within the receptor and produces, according to Equation (7), a corresponding output threshold power, K_d, which is called the "standard signal response power level". This particular output threshold power is defined as that output signal power, S_D, which has an appropriate relationship to the output noise power, N_D, such that desired signal performance quality is just achieved for the receptor. This discussion indicates that, in the idealized, interference-free environment, the receptor may have both signal power and internally generated noise power present at its detector input, a condition which is expressed by the following:

$$P_D = S_D + N_D = N_D\ (1 + S_D/N_D) \tag{8}$$

The input signal power at the detector in (8) can be thought of as constrained by the bandwidth of some filter device preceding the detector input while the noise power is constrained by the "effective noise bandwidth", B_n, of the receptor device itself. In the following discussion references to output power levels always refer to levels at the detector input.

The above relationship shows that the output signal power can be calculated as the product of an output noise power (a constant for a given receptor given by $N_D = G_o\ Fk\ T\ B_n$*) and the output signal-to-noise power ratio, $SNR = S_D/N_D$. It can generally be said that the output signal-to-noise power ratio governs the performance quality of a receptor and that a specific numeric value of the ratio, denoted $\overline{SNR}$, establishes the threshold signal power at the receptor's detector according to the following:

$$K = N_D \ \cdot\ \overline{SNR}$$

In particular, the "standard signal response power level", K_d, at the detector input is defined to be:

$$K_d \triangleq N_D \ \cdot\ \overline{SNR} \tag{9}$$

where the $\overline{SNR}$ value to be assigned is dependent upon the type of receptor involved and upon the criterion employed to judge its performance quality. Corresponding to the "standard signal response power level" defined above is a minimum value of receptor input power at a particular frequency, f_p, which just produces the threshold power level. This "minimum detectable signal" at the receptor input port is defined by:

$$P_d(f_p) \triangleq K_d/\beta(f_p) \tag{10}$$

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* This is a standard definition for output noise power as defined in numerous textbooks on communication receivers. The symbols are defined as follows:

G_o = the on-tune power gain - a numeric

F = receiver noise figure - a numeric

k = Boltzman's constant in watts per degree Kelvin per Hz

T = device temperature in degrees Kelvin

B_n = the device noise bandwidth in Hz

At the receptor tuned frequency, f_o, it is recognized that the quantity $\beta(f_o)$ is identically the tuned frequency power gain of the receptor, G_o, and the above definition of "minimum detectable signal" or "threshold sensitivity" takes the form normally employed in communication system calculations as follows:

$$P_d(f_o) = N_D\overline{SNR}/\beta(f_o) = G_o FkTB_n\overline{SNR}/G_o \qquad (11)$$

$$= FkTB_n\overline{SNR}$$

4.2.3 Minimum acceptable signal. In an actual system application of a receptor, there may exist numerous sources of unintentional or interference signals with which a desired signal must compete. These system generated interference signals can couple to the receptor input port by one or more of a variety of coupling paths and will produce an output power component at the receptor's detector which will influence the receptor's performance quality. The system design and the application of receptor devices in the system must provide for some interference tolerance. The amount of interference tolerance will be subject to tradeoffs but, in general, will be defined initially for each individual receptor based on some "minimum acceptable signal" performance criterion. A method for defining such an input desired signal level which reflects a tolerance for system induced interference is now developed.

The receptor output power (detector input) in the system environment contains an interference power component in addition to the thermal noise power and the desired signal power and is described simply as follows:

$$P_D = S_D + N_D + I_D = (N_D + I_D)\ [1 + S_D/(N_D + I_D)] \qquad (12)$$

Again, the output signal power, S_D, is seen to be calculated as the product of output noise-plus-interference power and a quantity called the output signal-to-(noise plus interference) power ratio, SNIR, where $SNIR \triangleq S_D/(N_D+I_D)$. In the system environment, it is necessary to establish the particular numeric value of this ratio, denoted $\overline{SNIR}$, which produces the "standard interference response signal power level", K_a, at the detector such that an acceptable performance quality results for the receptor. This new value of detector threshold power is accordingly defined as follows:

$$K_a \triangleq (N_D + I_D)\ .\ \overline{SNIR} \qquad (13)$$

This "standard interference response signal power level" has an associated receptor input port power level, $P_a(f_p)$ at an arbitrary frequency which is called the "minimum acceptable signal" and is given by:

$$P_a(f_p) \triangleq K_a/\beta(f_p) \qquad (14)$$

Since K_a is determined from the product of the combined thermal noise plus interference power with a $\overline{SNIR}$ value and since $\overline{SNIR}$ is likely to equal $\overline{SNR}$, it follows that $K_a > K_d$ is probably true in most cases.

4.2.4 Susceptibility Power Level. The discussion just preceding has established the particular signal power threshold at a receptor's detector that was tolerant of some system-induced interference power. This "standard interference response signal power level" had a corresponding "minimum acceptable signal" at the receptor input port defined by Equation (14) in which the detector threshold power level, K_a, was defined in Equation (13) in terms of an allowable $\overline{SNIR}$. The question next requiring an answer is: What is the tolerable level of interference power at the receptor's detector? This "standard interference response interference power level", K_s, will have an associated input port "susceptibility power level" at every frequency point in the spectrum given by:

$$S(f_p) \triangleq K_s/\beta(f_p) \tag{15}$$

The "EMI margins" calculated by IEMCAP will be seen to be the ratio of actual interference power level calculated by the program at the receptor input to the "susceptibility power level". A ratio greater than unity is said to be an interference condition; a ratio less than unity is said to be a compatible condition.

The following development defines the interference "susceptibility" in terms of the other quantities known about the receptor and defined previously. The development starts with Equation (13) where the output interference power, I_D, is now considered to be exactly the tolerable interference power or "standard interference response interference power level", K_s, at the detector as follows:

$$K_a = N_D\ (1 + K_s/N_D)\ .\ \overline{SNIR} \tag{16}$$

(this is just Equation (13) with I_D set equal to K_s)

Now, from (9), $N_D = K_d/\overline{SNR}$ so that

$$K_a/K_d = (1 + K_s\ .\ \overline{SNR}/K_d)\ .\ \overline{SNIR}/\overline{SNR} \tag{17}$$

Then,

$$(K_s/K_d)\ .\ \overline{SNR} = \left[(K_a/K_d)\ \ (\overline{SNR}/\overline{SNIR})\ -1 \right] \tag{18}$$

or, using Equations (9), (11), (14) and (15) in (18), there obtains:

$$\frac{S(f_p)\beta(f_p)}{P_d(f_o)\beta(f_o)} \ \overline{SNR} = \left[\frac{P_a(f_o)\beta(f_o)}{P_d(f_o)\beta(f_o)} \ \frac{\overline{SNR}}{\overline{SNIR}} \ - 1 \right] \tag{19}$$

Finally, use of the definition for "threshold sensitivity" given by Equation (11) in (19) yields:

$$S(f_p) = \frac{\beta(f_o)}{\beta(f_p)} \ FkTB_n \left[\frac{P_a(f_o)}{P_d(f_o)} \ \frac{\overline{SNR}}{\overline{SNIR}} \ -1 \right] \tag{20}$$

Equation (20) defines the "susceptibility" function of frequency in terms of input power ratios at the tuned frequency, f_o, the product of input thermal noise power with the on-tune power gain, $\beta(f_o) = G_o$, and the power transfer function, $\beta(f_p)$. The product of on-tune power gain with the input noise power, G_oFkTB_n is, of course, the output noise power, N_D (noise power at the detector input). Equation (20) demonstrates again that the susceptibility function is inversely proportional to the power transfer function in accordance with the definition given by Equation (15).

Evidently the susceptibility function of frequency is a curve similar to that shown previously in Figure 4, taking on power values described by Equation (20). Figure 6 shows, as functions of frequency, the three receptor input power quantities defined and discussed in this section. The receptor response characteristic for "minimum detectable signal", for "minimum acceptable signal" and for "susceptibility power level" are all identical functions of frequency except for constant power level displacement factors as indicated in Figure 6. These constant displacement factors are exactly the detector input power levels associated with each receptor input power quantity, divided by the on-tune power gain of the receptor in each case.

In general, as indicated in Figure 6 and in accordance with the preceding discussion, the "minimum acceptable signal" curve will be displaced upward from the "minimum detectable signal" since a higher level of desired signal will probably be necessary in order to tolerate some interference power in the receptor. It is also to be expected in most cases that the "susceptibility power level" curve will be displaced downward from the "minimum detectable signal" curve in the manner illustrated in Figure 6. Whatever the actual displacement direction or amount, the "susceptibility power level" at the tuned frequency will nearly always have a value different than the receptor "sensitivity" level (minimum detectable signal) and this "susceptibility power level" is the value that must be used in the IEMCAP input data for receptors instead of the "sensitivity" value that is presently specified (Reference 1).

4.3 RF receiver performance. The developments in the preceding paragraphs are elaborated upon in this section by reference to typical performance characteristics of RF receivers. The discussion here will focus attention on the detector section of RF receivers which governs their signal response behavior. Figure 7, which shows the separation of the typical receptor into two functional sections, will aid the discussion. The first section of the receptor is defined to include all of the linear input stages providing signal gain and frequency selectivity. All nonlinear effects are considered to reside in the detector.

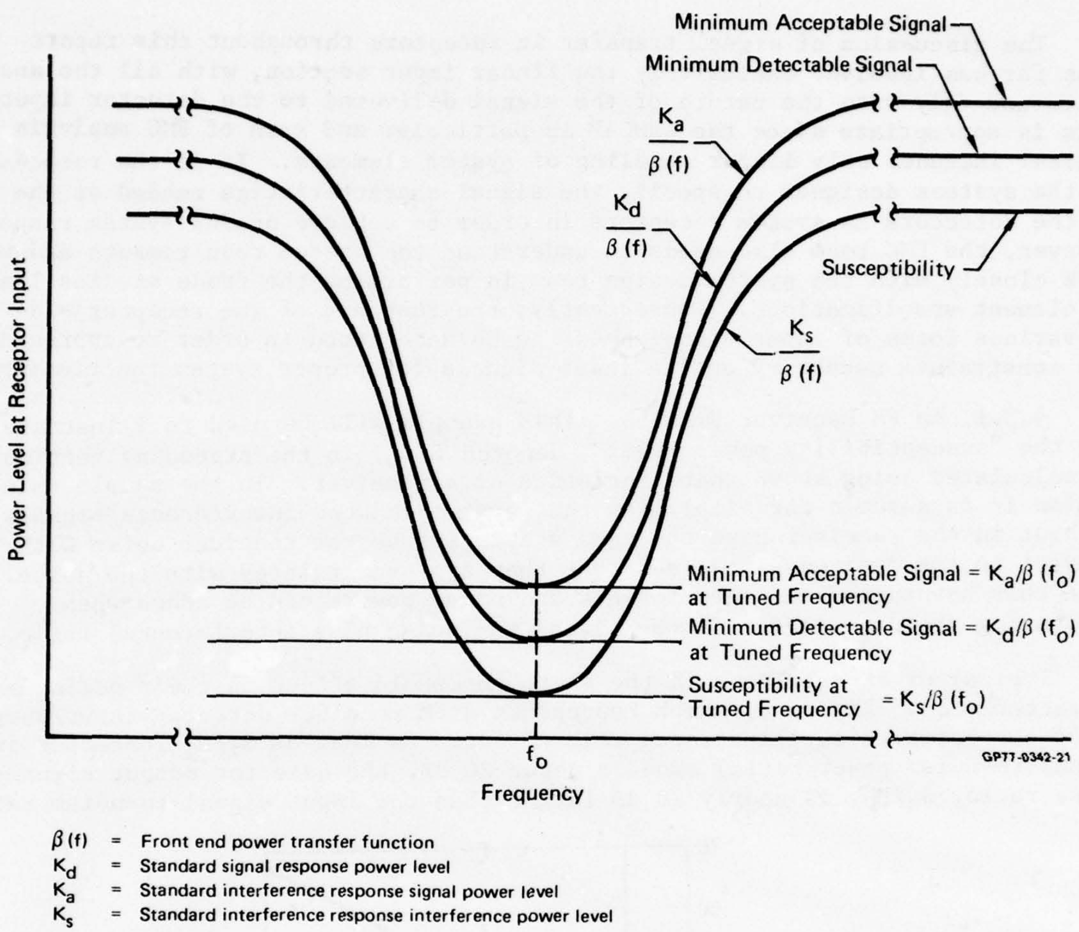

Figure 6. Power Level at Receptor Input for Constant Power at Detector Input

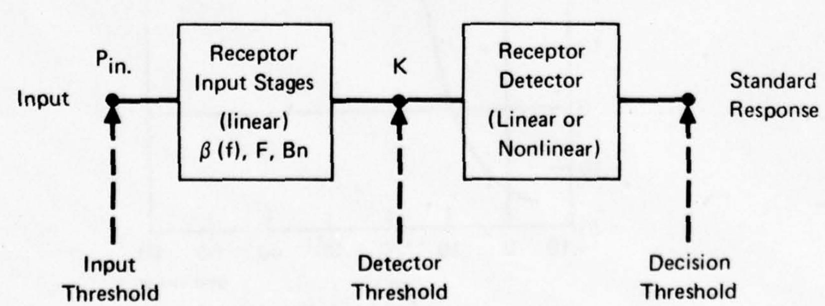

Figure 7. Two-Section Representation of a Receptor

The discussion of signal transfer in receptors throughout this report thus far has involved exclusively the linear input section, with all the analyses concerned only with the nature of the signal delivered to the detector input. This is appropriate since the IEMCAP in particular and much of EMC analysis in general includes only linear modeling of system elements. It is the responsibility of the systems designer to specify the signal characteristics needed at the inputs to the detectors in system receptors in order to achieve needed system responses. However, the EMC team also needs to understand the system requirements and will work closely with the system design team in performing the trade studies leading to element specifications. Consequently, the response of the receptor's detector to various forms of input signal needs to be understood in order to appreciate the constraints necessary on its input signals for proper system functioning.

4.3.1 An FM Receiver Example. This example will be used to illustrate how the "susceptibility power level", denoted $S(f_o)$ in the preceding section, is calculated using known characteristics of a receiver. In the sample calculation it is assumed for simplicity that system-induced interference signals present in the receiver have the same statistics as the receiver noise with respect to the desired signal and that they are uncorrelated with the noise. With this assumption the interference and noise powers can be added when evaluating the denominator of the signal-to-(noise plus interference) ratio.

Typical of FM receivers is the sharp threshold effect in their performance characteristic. Figure 8, which represents a FM receiver detector input/output power characteristic, illustrates this effect. As long as S_i/N_i (detector input signal-to-noise power ratio) exceeds about 20 dB, the detector output signal-to-noise ratio, S_o/N_o, is nearly 20 dB larger than the input signal-to-noise ratio.

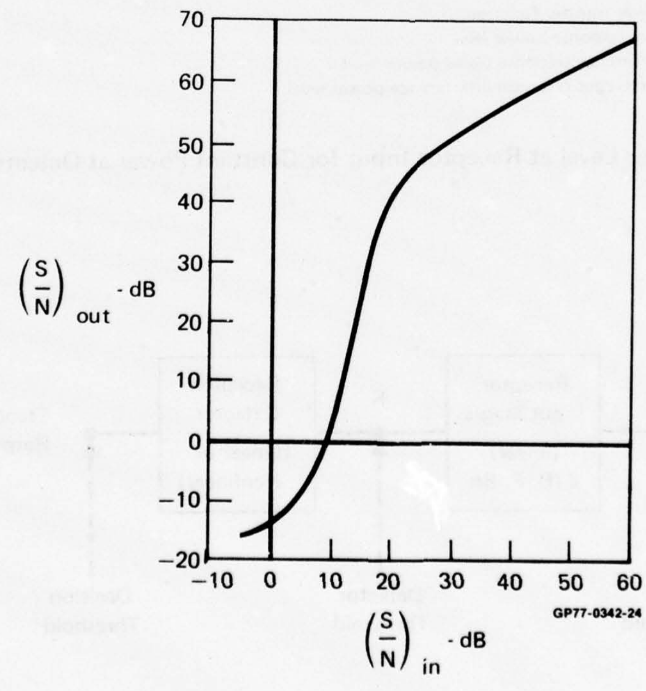

Figure 8. Typical FM Receiver Performance Curve

With smaller values of S_i/N_i, performance degrades rapidly, though not necessarily unacceptably. Since it is usually desirable to operate above this threshold or knee of the performance curve, it is assumed in this example that the minimum acceptable S_i/N_i ($\overline{SNR}$ in the preceding discussion) should be 20 dB. It will also be assumed that the sensitivity or "minimum detectable signal", $P_d(f_o)$, at the receiver input terminals, in the absence of interference, is -90 dBm and that this produces a signal power (standard response power level), K_d, at the detector input of -30 dBm (receiver power gain, G_o, of 60 dB). In order to achieve $\overline{SNR} = S_i/N_i$ = 20 dB for this "minimum detectable signal", it follows that the noise power at the detector input is -50 dBm.

Now assume that this FM receiver has been selected for use in a new system in which system-induced interference must be tolerated while realizing acceptable performance of the receiver. That is, noise-like interference will be present at the receiver input in addition to some "minimum acceptable signal" and the thermal noise. It is assumed that the system design calculations have shown that the "minimum acceptable signal", $P_a(f_o)$, at the receiver input will be -84 dBm. This signal will appear at the detector input with a power level, K_a, of -24 dBm. Such a signal, in the absence of interference, would produce an input signal-to-noise ratio, S_i/N_i, at the detector of 26 dB. This is seen to provide a 6 dB margin above the 20 dB required $\overline{SNR}$ assumed for the example. With the assumption that the interference will combine with the noise additively and that the required signal-to-(noise plus interference), $\overline{SNIR}$, must be identical to the $\overline{SNR}$ for the interference-free condition, the "susceptibility power level", $S(f_o)$, can be immediately calculated using Equation (20) of the preceding section as follows:

$$\overline{SNR}/\overline{SNIR} = 1$$

$$P_a(f_o)/P_d(f_o) = 4 \quad (-84 \text{ dBm} +90 \text{ dBm} = 6 \text{ dB})$$

$$\beta(f_o)FkTB_n = G_oFkTB_n = 10^{-8} \text{ watts } (-50 \text{ dBm})$$

$$\beta(f_o)FkTB_n/\beta(f_o) = 10^{-14} \text{ watts } (-110 \text{ dBm})$$

$$S(f_o) = [\beta(f_o)/\beta(f_o)]\ FkTB_n \left\{ [P_a(f_o)/P_d(f_o)]\ [\overline{SNR}/\overline{SNIR}] - 1 \right\}$$

$$= 3 \times 10^{-14} \text{ watts } (-105.2 \text{ dBm})$$

Thus it is seen that the "susceptibility power level", the IEMCAP input data quantity required for a receptor in a system EMC analysis, provides a tolerable input interference power level in the system environment of three times the receiver input noise power for this FM receiver example.

With reference again to the hypothetical receiver power transfer curves of Figure 6, the above result says that the "susceptibility power level" at the receiver front end should be down approximately 21 dB from the "minimum acceptable signal" at the tuned frequency of this receiver (-105.2 dBm + 84 dBm). The "susceptibility power level" is also down approximately 15 dB from the "minimum detectable signal" (-105.2 dBm + 90 dBm) or the "sensitivity" level of this receiver.

It is considered instructive to approach the susceptibility calculation for the FM receiver from a different perspective using the relationships developed in Section 4.2. The result, of course, will be identical to that obtained in the numerical example above but the approach used should provide some additional insight into the situation. All of the assumptions made in the preceding calculation will also apply in the following numerical development.

The noise power at the input to the receiver detector is:

$$N_D = 10^{-8} \text{ watts } (-50 \text{ dBm})$$

$$SNR = S_D/N_D \text{ (interference free)} = 4\text{x}10^2 \ (-24 \text{ dBm} + 50 \text{ dBm} = 26 \text{ dB})$$

$$S_D = N_D \text{ x } SNR = 4 \text{ x } 10^{-6} \text{ watts } (-24 \text{ dBm})$$

$$\overline{SNIR} = \overline{SNR} = 10^2 \ (20 \text{ dB})$$

$$K_a = S_D = \overline{SNIR}(N_D + I_D) = 4\text{x}10^{-6} \text{ watts } (-24 \text{ dBm})$$

$$(N_D + I_D) = K_a/\overline{SNIR} = 4\text{x}10^{-6}/10^2 = 4\text{x}10^{-8} \text{ watts } (-74 \text{ dBm})$$

$$K_s = I_D = (N_D + I_D) - N_D = 4\text{x}10^{-8} - 10^{-8} = 3\text{x}10^{-8} \text{ watts } (-45.2 \text{ dBm})$$

$$S(f_o) = K_s/\beta(f_o) = K_s/G_o = 3\text{x}10^{-8}/10^6 = 3\text{x}10^{-14} \text{ watts } (-105.2 \text{ dBm})$$

As expected, the above susceptibility power level result obtained from calculations with receiver detector input power levels, has the same value as that obtained using front end power levels in Equation (20). The information brought forth by this latter calculation that will often be useful in practical applications is knowledge about the signal and interference power levels at the detector input, S_D and I_D. These power levels could also be obtained from the input power quantities, $P_a(f_o)$ and $S(f_o)$ respectively, obtained in the previous sample calculation, by multiplying these by the on-tune power gain, G_o.

The ratio of detector input signal-to-interference powers, S_D/I_D, will often be valuable to systems and EMC engineers when establishing acceptable performance criteria for receptors operating with interference signals present, using the "receptor performance curves" when these are available as discussed in the next section. In the present example the S_D/I_D for the hypothetical FM receiver is seen to be approximately 21 dB (-24 dBm + 45.2 dBm).

Evaluations of the "Susceptibility" criterion for other types of receivers may not always employ the output signal-to-noise ratio as the performance criterion. Some other receiver types and their associated performance criteria include the following:

1) AM receivers: output signal-to-noise versus input signal-to-noise.

2) Digital communication receivers: Probability of error versus input signal-to-noise ratio,

3) Radar receivers: Probability of detection versus input signal-to-noise ratio (assuming a fixed false alarm probability),

4) Voice communications: articulation score versus input signal-to-noise ratio,

5) TV communications: TASO subjective scoring method relative to a picture quality versus input signal-to-noise ratio.

4.4 Susceptibility quantification for general interference. Consideration should be given to the fact that the statistics of a particular interference signal may not be the same as that of the front end noise relative to the desired signal and further, some interference types may be more offensive than others to the desired signal. Here one cannot solve for the standard interference response power level by merely representing the interference power as being linearly proportional to the front end noise and thus using standard signal-to-noise performance curves for its determination. One should resort here to tests or non-linear computer codes relating to the specific modulation/demodulation characteristics of the given receptor. The results of this approach are generally presented in curves similar to Figure 9, which gives performance scoring versus input signal-to-interference ratio for constant signal-to-noise ratios. Using such curves one can then determine a number of standard interference power levels, each associated with specific interference modulation types.

A proposed approach for utilization of such performance data is that, at the outset of the IEMCAP usage on a particular system, the EMC engineer surveys the system for prospective interference to a particular receptor, picking the most offensive one from a signal-to-interference ratio standpoint, thus defining a maximum standard interference response interference power level for an initial run. Refinements to a given receptor's standard interference response interference power level can be subsequently made if the initial run shows the preponderance of interference comes not from the most objectionable signal from a detector standpoint, but from some other source.

Work related to considerations of signal-to-interference statistics and non-linear effects of interference analysis have been carried out by the Electromagnetic Compatibility Analysis Center and results in a form similar to Figure 9 are documented in the Communication Electronics Receiver Performance Degradation Handbook, Reference 2.

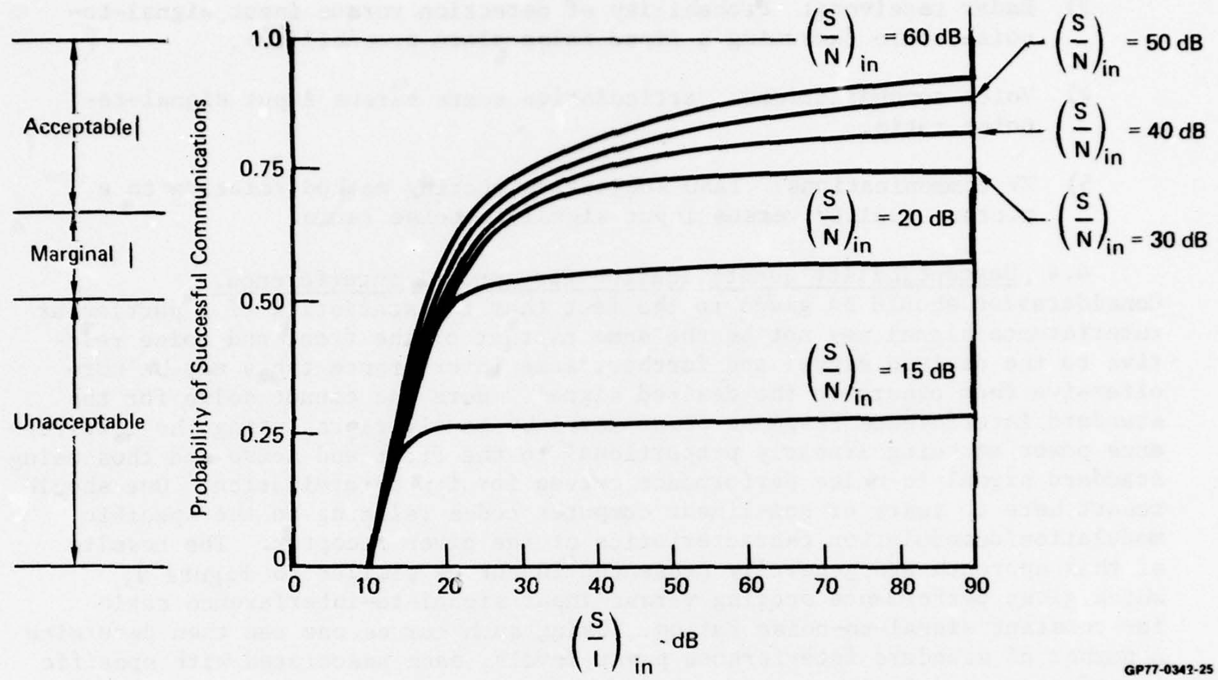

Figure 9. Output Performance vs Input Signal-to-Interference Ratio for Constant Signal-to-Noise Ratio

5. PROCEDURE FOR CORRELATION OF THE INTEGRATED MARGIN WITH TEST DATA

An experiment is described in this section which may be used to demonstrate the physical meaning of the integrated EMI margin (I.M.) calculated by the IEMCAP. The experiment will also serve to provide data for correlation with the IEMCAP numerical computations by careful modeling of the parameters of the experiment into the IEMCAP, running the program and comparing its output data with the test data.

As discussed previously, there exists a power level for power sensitive receptors, measured at the detector input, due to unrequired system emissions which, if exceeded, will cause the receptor to deviate from an acceptable required signal performance. This power level has been defined as the "standard interference response power level". All IEMCAP calculations are relatable to this interference threshold power level. The IEMCAP actually utilizes a "susceptibility" power level which is just the "standard interference response power level" transformed to the receptor input port.

The susceptibility level is used in the IEMCAP to normalize the input interference power spectral density in the integration computation leading to the quantity called the integrated EMI margin. If the value of the integral, expressed in decibels, exceeds 0dB, an interference condition is said to exist. This normalized integration procedure is equivalent to comparing the interference power level, measured at the detector, to the standard interference response power level.

The purpose of the proposed experiment is to demonstrate that this normalized integral approach to predicting power ratios at the detector input is valid for power - vulnerable equipments and that the resultant IEMCAP integrated margin can be correlated with the measured data. The experimental procedure involves use of a number of independently variable signal generators simultaneously coupling into a receptor having a detector whose output is linearly proportional to power. Such equipment is usually available in an EMC laboratory.

The power - vulnerable receptor can be configured from a standard EMI test receiver, such as an Empire Devices NF-105, with an average power detector (thermistor or bolometer) connected to the post IF stage as shown in Figure 10. Using this receptor configuration, it is evident that the meter reading is directly proportional to the detector input power level.

The signals for input to the NF-105 can be derived from a combination of tunable CW signal generators (which may also be modulated) combined by means of a resistive combiner with typical resistance as shown in Figure 11. The resistance values suggested for the combiner will provide greater than 60 dB isolation between sources.

The test procedure to be followed is to first use one of the CW generators and, by varying its frequency and amplitude, determine a CW input power function for a constant receiver output, such as that sketched in Figure 12. This CW input power selectivity function can then be used to validate the system approach in the IEMCAP by injecting 2 or more signals at different frequencies and verifying that their combined effect on the receptor, measured at the detector, actually corresponds to the normalized integration of the interfering signals at the receptor input based on the susceptibility function.

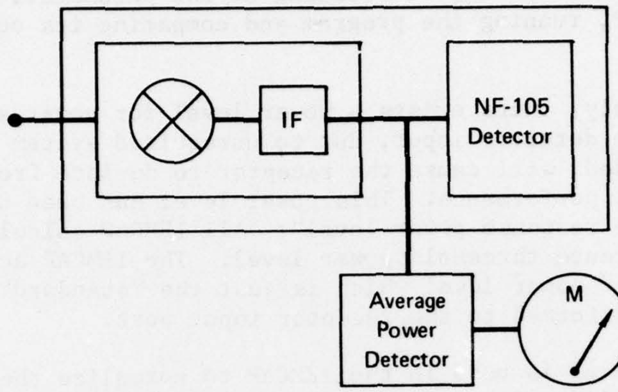

Figure 10. NF-105 with Post IF Average Power Detector

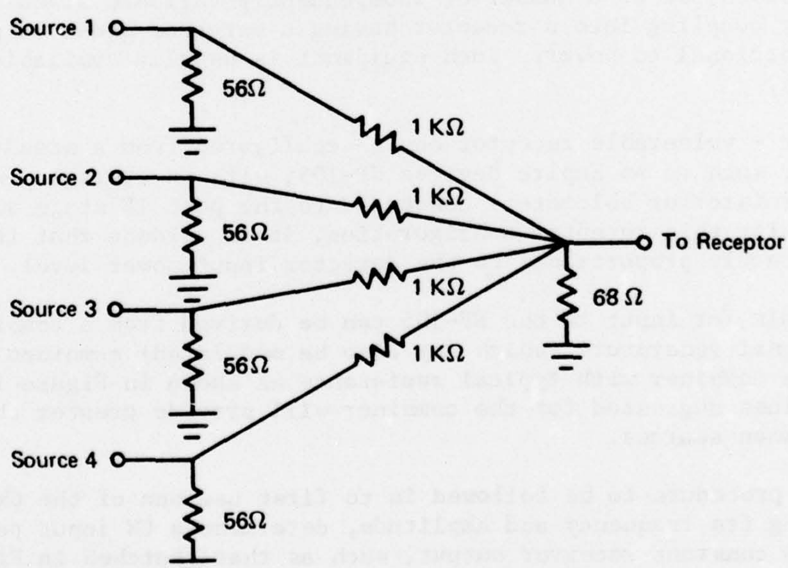

Figure 11. Resistive Combiner for up to Four Signals Input Simultaneously to a Receptor

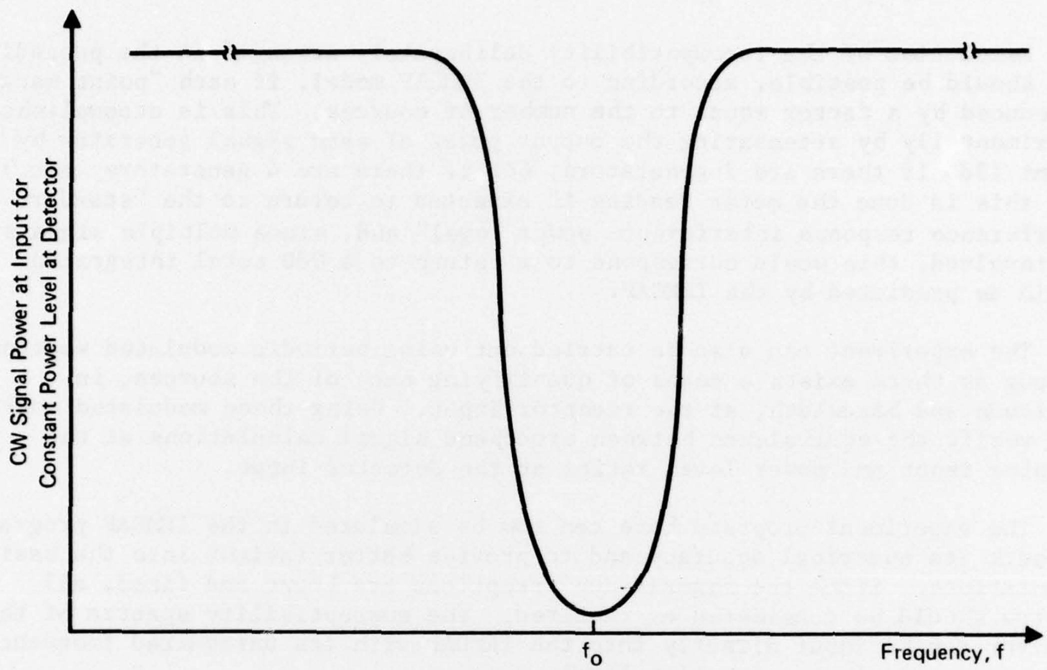

Figure 12. CW Input Power Response of a Receiver

The input CW power response function can be defined by choosing a specific receptor meter reading as the "standard interference response interference power level" and measuring as a function of frequency the single source amplitude at the receptor input which produces that designated receptor response. In keeping with EMC terminology, since the meter response has been designated the standard interference response, this input power function is defined to be the "susceptibility function" of the receptor for this experiment.

The next stage of the experiment is designed to demonstrate experimentally the IEMCAP point margins and total integrated margin. This is done by using two or more signal generators simultaneously with each operating at different frequencies and with their power levels adjusted to produce just the receptor input power level corresponding to the "susceptibility curve" previously established for the receptor. Thus, each generator individually delivers just the amount of power at the detector to produce the "standard interference response interference power level" established earlier in the experiment. This corresponds, in the IEMCAP terminology, to a 0dB point margin at each of the generator signal frequencies. Under these conditions the receptor power meter reading is expected to be a factor of N times the originally chosen reference power level, where N is the number of signal sources. Assuming this is the case, the result corresponds to an incompatibility on the basis of the IEMCAP "total integrated margin". If indeed the receptor response power level is equal to the "standard interference response interference power level" times the number of sources, the equivalence between the integrated margin, evaluated at the receptor input by the IEMCAP, and power ratios at the detector has been demonstrated experimentally.

Resolution of the incompatibility deliberately arranged in the preceding step should be possible, according to the IEMCAP model, if each "point margin" is reduced by a factor equal to the number of sources. This is accomplished experimentally by attenuating the output power of each signal generator by that amount (3dB if there are 2 generators, 6dB if there are 4 generators, etc.). When this is done the meter reading is expected to return to the "standard interference response interference power level" and, since multiple signals are involved, this would correspond to a return to a 0dB total integrated margin as predicted by the IEMCAP.

The experiment can also be carried out using periodic modulated sources so long as there exists a means of quantifying each of the sources, in amplitude and bandwidth, at the receptor input. Using these modulated sources will verify the equivalence between broadband signal calculations at the receptor input and power level ratios at the detector input.

The experiment proposed here can now be simulated in the IEMCAP program to check its numerical accuracy and to provide better insight into the basic computations. Since the signals and receptions are known and fixed, all spectra should be considered as required. The susceptibility spectra of the receiver can be input directly into the IEMCAP with its unrequired frequency region set to a large rejection level.

Since the IEMCAP cannot handle direct coupled input signals to receptors, each of the signal source spectrums must be simulated as coupling through some fictitious coupling medium. This is easily accomodated by specifying all the sources as RF ports connected to the same antenna and specifying the receptor as an RF port connected to an antenna in the very near field so that the transfer function between source and receptor is a known constant. Each source input power can then be multiplied by the reciprocal of that constant. Allowing for this source adjustment and setting the unrequired emission levels to a negligible level one can then proceed with the numerical simulation.

Setting each of the signal sources to a value that produces the susceptibility power level at the input should produce IEMCAP outputs comparable to the experimental results. Since each portion of the input spectra results from different sources the program "total integrated margin" output is equivalent in principle to the experiment "integrated margin" while the program "integrated and point margins" are comparable to the experiment "point margins".

Ideally the program outputs for all the sources inputting the susceptibility power level should be zero dB point and integrated margins and a total integrated margin of $10 \log_{10} N$ dB. Subsequent running of IEMCAP with the emitter amplitudes reduced by 1/N as prescribed in the experiment should ideally product a zero dB total integrated margin. Comparison with actual IEMCAP outputs will provide a check on the numerical accuracy of the integrated margin calculation.

6. INTEGRATED MARGIN AS EMC FIGURE OF MERIT.

The discussion in this section examines the reliability of the integrated EMI margin (I.M.) as an indicator of EMI/EMC of system elements. Within certain limitations that are discussed, the general conclusion is that the I.M. is as good for this purpose as the data available as input to the IEMCAP for modeling the system elements. This conclusion is supported to a high degree by the results obtained in the assessment of the compatible F-15 weapon system performed on the present program. While a number of incompatibilities were predicted for the F-15 system by the IEMCAP, most of these are explainable or at least found highly questionable, because of insufficient test data with which to model the system elements. Wherever good test data existed in the F-15 assessment, the predictions (extensively using the I.M.) were also generally good. Where the predictions were poor, under circumstances of good input data, they were usually traceable to situations which could not be adequately treated by the existing models in the IEMCAP.

Prior to its being exercised against the F-15 system, there had been a belief that the IEMCAP would over-predict interference to a substantial extent. This expection was not verified however. The bases for these original concerns included the various worst case assumptions in the program system model and such factors as the assumptions about wire spacings in bundles. The influences of these effects are not fully established at this point, although the sensitivity study performed on the F-15 mini-system tended to dispel many of the earlier concerns.

There is strong evidence, as brought out in previous sections that, given good modeling of the spectra and of the coupling modes in a system, the I.M. calculated by the IEMCAP is a proper indicator of EMI/EMC for power vulnerable receptors. It is found, however, that there are certain receptors in systems, probably coming into more widespread use as technology advances, that are not adequately represented by the power vulnerablity assumed in the IEMCAP system model. These threshold vulnerable devices must have more information about their actual modes of excitation and the IEMCAP should make provisions for an option capable of predicting the system effects on such devices. An approach to providing the IEMCAP with a logical alternative analysis approach, using peak current margins, for threshold devices has been suggested herein. A key aspect remaining to be adequately treated is the proper assignment of susceptibility levels for such devices. There appears currently to be a lack of consensus in the electronics community about the degree of vulnerability ot these types of system elements to EMI upset.

The assessment of the validity of the I.M. as an indicator of EMI/EMC during the IEMCAP F-15 validation program involved extensive exercising of the Comparative EMI Analysis Routine (CEAR) portion of the IEMCAP. This use of the CEAR, while providing strong indications of the reliability of the I.M. as an EMC figure-of-merit for known equipment, does not fully emphasize all of the precautions required to be exercised by a user in the development of a new system using the specification generation routine (SGR). In this important application of the IEMCAP, the I.M. requires very careful evaluation in relation to other program outputs and should not be relied upon exclusively as the indicator of EMI/EMC. The reasons for this precaution have been elaborated previously, but certainly include the need for awareness of the possibility of over-specifying equipment spectrum suppression, in addition to the normal emphasis on EMC. Very often in this situation, where spectra are largely unknown, the point margins and total point margin calculated by the IEMCAP are very useful in pinpointing sources and spectral regions of potential EMI and will reveal performance and cost effective approaches for assuring EMC that are at least as valuable as the I.M. in this regard.

In summary, a number of factors combine to affect the reliability and accuracy of the integrated EMI margin (I.M.), calculated by the IEMCAP, as a measure of EMI/EMC. In general, these factors vary during the life cycle of the system, with the accuracy improving as the system matures. The key factors affecting accuracy of a new system are as follows:

a) Errors in the spectral data estimates for equipments not yet developed or tested; estimated standard deviation of error (e.s.d.e.) in I.M. of 20 dB.

b) Measurement data errors for the spectra of existing equipment plus variations from equipment to equipment; e.s.d.e. in I.M. of 3 dB.

c) Input data errors resulting from inexact knowledge of wire locations and locations of apertures, antennas and equipment boxes; e.s.d.e. in I.M. of 6 dB.

d) Inaccuracies of the IEMCAP coupling and spectrum mathematical models; e.s.d.e. in I.M. of 10 dB.

e) Errors due to IEMCAP approximations in the spectra, coupling and system models; e.s.d.e. in I.M. of 3 dB.

Treating the error in the I.M. as a sum of errors which are random and independent of each other, the resulting standard deviation of the error is obtained as the square root of the sum of the squares of the individual e.s.d.e.'s, yielding an e.s.d.e. of the I.M. of approximately 24 dB.

The maturity of a system is seen to be a definite factor in the reliability of the I.M. in predicting EMI/EMC. The more that is known about the emission and susceptibility spectra and about the mechanisms of coupling of system elements, the closer the I.M. comes to being a true measure of electromagnetic compatibility in the system.

REFERENCES

1. Intrasystem Electromagnetic Compatibility Analysis Program, Volume I - User's Manual Engineering Section; RADC-TR-74-342, Final Report, December 1974, (A008526).

2. Communications/Electronics Receiver Performance Degradation Handbook (Second Edition); ESD-TR-75-013, Final Report, August 1975

APPENDIX A

An Introduction to the IEMCAP

This appendix is a description of the IEMCAP program, the capabilities for which it is designed, and its basic approach to system EMC analysis.

The IEMCAP is a computerized analysis program to facilitate the practical implementation of EMC at all stages of an Air Force system's life cycle, from conceptual studies of new systems to field modification of old systems. This capability is applicable for use in ground, aircraft and space/missile systems. The major areas to which this program addresses itself in attaining this objective are specification generation, waiver analysis, design change evaluation, and trade-off analysis. To achieve all of the above tasks, the computer program is designed with the flexibility to perform compatibility analysis at design stages ranging from a conceptual system configuration to a well-defined system.

The program provides the EMC engineer with a variety of analysis capabilities for use in all phases of the system development cycle from conceptual feasibility studies to field modification of existing systems. Presently, rigid military specifications are used to control the generation of and susceptibility to Electromagnetic Interference (EMI). The same specifications are applied to an individual relay, to a complex spaceborne rendezvous radar, to a one-shot missile, to a long-lived, multi-purpose fighter aircraft, and to a ground-station complex covering many acres. To cover such a wide range of applications, the military specifications must be general and are usually limited to worst-case conditions. Such general-purpose specifications do not provide for particular system and installation characteristics, and therefore they do not guarantee total system EMC and often result in overdesign. To provide for cost effective EMC this program combines a versatile file management system and state-of-the-art mathematical models to perform the following tasks:

- The program generates EMC specifications to supplement or replace MIL-STD-461, or MIL-I-6181.
- The program assesses the impact of these specifications.
- The program provides information on design parameters that assist the EMC and design engineers in establishing a compatible systems design and in making trade-off decisions.
- The program determines the effect of design changes and evaluates the feasibility of new concepts.

IEMCAP Data Organization

Complex defense systems contain vast numbers of emitters and receptors of electromagnetic energy. To organize these into a form convenient for collection and utilization by the user and the IEMCAP program, a hierarchy structure is defined. The system (aircraft, spacecraft, or ground) is divided into subsystems which are groups of equipments performing related tasks.

The physical boxes comprising the subsystem are defined as equipment cases, and electromagnetic energy may enter or leave these equipment cases via ports. Ports are designated as emitters or receptors (or both). An emitter port generates electromagnetic energy, and a receptor port is susceptible to electromagnetic energy.

Ports may be intentional or unintentional. An example of an unintentional port is leakage into or out of an equipment case. An example of an intentional port is a connector pin through which AC power, signals, etc. are brought into or out of the equipment.

Basic Analysis Approach

All intentional ports must generate and/or receive certain types of signals to perform their intended function. The signals or responses which are intentionally generated and coupled from port to port are called operationally required and cannot be altered without affecting system operation. In addition to the required signals, there may be additional undesired outputs and/or responses. These are called operationally non-required. For example, an emitter can have non-required outputs in the form of harmonics, and a receptor can have an undesired response in the form of an image response.

An incompatibility is said to exist when sufficient signal from an emitter port, or ports, is unintentionally coupled to a receptor port to exceed its susceptibility threshold. Required signals and responses, by definition, cannot be restricted by EMC specification. The non-required signals and responses are spurious and can be controlled; that is, limits can be set for them such that the system is compatible. These limits are called EMC specifications. Ideally, if all ports have no emissions and susceptibilities exceeding these limits, the system is compatible. An important task of IEMCAP is the generation of a set of specification limits tailored to the specific system under analysis.

The emissions and susceptibilities, both required and non-required, are represented in IEMCAP by spectra. For each emitter port, a two-component spectrum represents the emissions produced over the frequency range. The broadband component represents continuous emissions, which vary slowly with respect to frequency; while the narrowband component represents discrete emissions, which vary rapidly with respect to frequency. Thus, each emitter can be considered to have two spectra: broadband and narrowband.

For each receptor, a spectrum represents the susceptibility threshold over the frequency range. The susceptibility level is defined as the maximum interfering signal, at a given frequency, for acceptable receptor performance.

For each intentional port, a portion of the frequency range is defined as the required range. All signals within this range are required and cannot be adjusted. Outside this range limits may be set for the maximum emission and minimum susceptibility levels. Within the required range, the spectrum is defined by a mathematical model of signal level versus frequency. This can be either from equations of the frequency domain representation of the signal or directly from a user-defined spectrum. Outside the required range, assumed levels are used for the port spectra. During specification generation, if these assumed spectrum levels cause interference, they are adjusted such that there is compatibility. By adjusting the spectra of emitters and receptors for compatibility, the maximum non-required emission and minimum susceptibility levels are obtained which will produce a compatible system. To prevent too stringent specifications from being generated, each spectrum has an adjustment limit. While any values could be used for the initial non-required spectra, IEMCAP uses the limits of military EMC specifications MIL-STD-461A and MIL-I-6181D. The initial levels may be relaxed or tightened from these if desired.

The general approach in performing the various tasks is two-fold. First an emitter-receptor port pair is selected and their type, connection, wire routing, etc. are quickly examined to determine if a coupling path exists. If a path exists the received signal is computed at the receptor and compared to the susceptibility level. In addition to the emitter-receptor port pair analysis, the program also computes the total signal from all emitters coupled into each receptor acting simultaneously.

Representation of Port Spectra

IEMCAP is required to analyze a large number of ports with reasonable run times and reasonable computer core memory requirements. At the same time, it must quickly evaluate the coupling from any type of emitter port into any type of receptor port. For specification generation, the spectra must be easily adjustable at the frequencies where incompatibilities are found as well as allow efficient incorporation of further adjustments. For trade-off and waiver analyses, the spectra and interference of modified ports must be efficiently compared to those from previous runs. Also, the spectra must be stored on files and readily used for future analyses.

In view of the above criteria, IEMCAP uses a sampled spectrum technique in which each spectrum amplitude is sampled at various frequencies across the range of interest. Considering the requirement of MIL-STD-461A of 3 frequencies per octave from 30 Hz and 18 GHz, this required approximately 90 sample frequencies. This is a reasonable resolution for EMC specifications in which limits of emission and susceptibilities are set and can apply over large regions of the spectrum. (If greater resolution is desired, IEMCAP allows the user to specify specific frequencies). To avoid missing narrow peaks between sample frequencies, IEMCAP samples the spectrum in the interval half-way between the sample frequency and each of its neighboring sample frequencies. For emission spectra, the maximum in the interval is used, and for susceptibility spectra the minimum is used. This effectively quantizes the spectra with respect to the sample frequencies. To minimize core memory and data file size requirements, a table of sample frequencies is defined for an equipment, and all spectra of ports within that equipment are quantized to the tabulated values.

The equipment frequency tables can be defined using two options. First, the user may specify the upper and lower frequency limits, the maximum number of frequencies (up to 90), and the number of frequencies per octave. The program then generates a table of geometrically spaced frequencies within the specified limits. Optionally, the user may specify the upper and lower frequency limits, the maximum number of frequencies and a number of specific frequencies (up to the maximum number) of interest. The program then generates geometrically spaced frequencies to fill in the number of frequencies not specified. For example, if the maximum number of frequencies to be used is 90 and 10 are user specified, the program generates 80 geometrically spaced frequencies over the specified frequency range and inserts the 10 user frequencies at the appropriate places. (The number of frequencies per octave is ignored if the latter option is used.)

The range of frequencies covered by the analysis is controlled by the user. The program will accept any range from 30 Hz to 18 GHz, but if desired, the user may concentrate all 90 frequencies over a smaller interval within this range.

Each port is categorized by function into one of six types, RF, power, signal, control, electro-explosive device, and equipment case, each type having its own subinterval of frequencies within the overall frequency range, adapted from MIL-STD-461/462 ranges for the port function. The non-required spectrum model routines generate zero emission and essential infinite susceptibility outside these sub-intervals.

Thus, IEMCAP represents the spectra as amplitudes within up to 90 contiguous intervals across the frequency range of interest quantized to the sample frequencies. The program is divided into two sections, the Input Decode and Initial Processing Routine (IDIPR) and the Task Analysis Routine (TART) each running in approximately 64 to 67K (words) of core memory. One section of the program contains the data management and spectrum model routines, and the other contains the analysis and transfer model routines. Each section is executed separately so that both are not in core at one time.

IEMCAP System Model

The system model for IEMCAP employs the standard EMC approach of identifying all ports in the system having potential for undesired signal coupling. These ports are divided into arrays of emitter ports and of receptor ports having identifiable coupling paths.

The mathematical basis for IEMCAP is the linear relationship for power coupled from an emitter, through a transfer medium and received by a receptor. A form of the general communication theory equation is used relating power spectral density at the detector of a receptor to power spectral density present at an emitter's output port. The ratio of the total power at the detector (obtained by integration) to a threshold power level, is used as a relative measure of interference. If this ratio, defined as the integrated EMI margin, is greater than one, an incompatible situation is said to exist.

APPENDIX B

A Proposed Treatment For Threshold Devices

An alternative approach to EMI assessment, based on peak voltage or current levels is presented here. The computer program IEMCAP, could be modified to accept this peak level formalism for those devices characterized by peak responses.

The response of a threshold vulnerable receptor can be characterized in terms of a peak level (current or voltage) delivered to the detection function of the receptor. This level is then related to the receptor input and used to define a current or voltage susceptibility function, relating the susceptibility at any frequency to the susceptibility at the tuned frequency.

Expressing the current time waveform as a Fourier integral (valid only for a deterministic signal), an upper limit to the peak value is obtained from the absolute value of the integrand according to the following:

$$i(t) = \int_{-\infty}^{\infty} I(f)\, e^{j\omega t}\, df \leq \int_{-\infty}^{\infty} \left| I(f)\, e^{j\omega t} \right| df$$

$$i(t) \leq \int_{-\infty}^{\infty} \left| I(f) \right| \cdot \left| e^{j\omega t} \right| df = \int_{-\infty}^{\infty} \left| I(f) \right| df$$

where I(f) is the current spectrum in amps per Hertz.

This expression for an upper bound on the current provides a justification for using a current spectrum formulation in an estimate of the peak current i_p or voltage v_p delivered to the receptor detection function; the peak voltage is related to the peak current by the load resistance, $v_p = Ri_p$.

Following is an analytical approach to estimating peak level interference responses of receptors. The approach is of the same general form currently employed in the IEMCAP for assessing interference signal average power effects. Let:

$I_j(f)$ = the current spectrum of the j^{th} emitter (amps/Hz)

$t_{ij}(f)$ = the current transfer function between the j^{th} emitter port and the i^{th} receptor port (unitless)

$h_i(f)$ = the linear current transfer function of the i^{th} receptor (unitless)

$T_i(f)$ = the susceptibility of the i^{th} receptor port as a function of frequency (amps)

Now, define a detector peak threshold level of current due to interference signals, i_s, which, if exceeded, results in degradation of the receptor's desired signal performance. This level is related to the receptor front end susceptibility level T(f) by the receptor linear transfer function $h_i(f)$ as follows:

$$i_s = T_i(f)\ h_i(f) \tag{1}$$

or,

$$T_i(f) = i_s/h_i(f)$$

At the on-tune frequency, f_o, this relationship becomes:

$$T_i(f_o) = i_s/h_i(f_o)$$

Thus, $T_i(f_o)$, the input port current susceptibility level at the on-tune frequency, is equal to the detector peak current threshold divided by the receptor transfer function at that frequency.

Using the preceeding definitions, the integral of the current spectrum $I_j(f)$, emanating from emitter j, coupled through the current transfer function $t_{ij}(f)$, and transferred through the input stage of receptor i to its detector input is written as follows:

$$i_D = \int_{f_a}^{f_b} I_j(f)\ t_{ij}(f)\ h_i(f)\ df$$

where,

- i_D = peak current level due to interference received at the input to the receptor's detector in the frequency range from f_a to f_b
- f_a = the lowest frequency in a range of interest
- f_b = the highest frequency in a range of interest

Dividing through by the current threshold level at the detector, and incorporating the relationship expressed in Equation (1), there results an expression for an EMI margin, the ratio of the peak current level at the detector to the threshold level:

$$\frac{i_D}{i_s} = \int_{f_a}^{f_b} I_j(f)\ t_{ij}(f)\ h_i(f)/i_s\ df$$

$$\frac{i_D}{i_s} = \int_{f_a}^{f_b} I_j(f)\ t_{ij}(f)\ h_i(f)/[T_i(f)\ h_i(f)]\ df$$

$$\frac{i_D}{i_s} = \int_{f_a}^{f_b} I_j(f)\, t_{ij}(f)/T_i(f)\, df \tag{2}$$

Thus the EMI margin can be expressed as the integral of the interference current spectrum at the input terminals divided by the current susceptibility level at the input terminals. The integrand in Equation (2) is identified as a "margin density" expressing the incremental frequency contributions to the current margin computations. Point Margins, integrated margin, total point margin and total integrated margin can be defined on a peak current basis in complete analogy with the corresponding quantities defined in the IEMCAP currently on an average power basis.

"Point current margins" (P.C.M.) are obtained by carrying out the integration over some suitable bandwidth, BW, with the following result:

$$\begin{aligned} \text{P.C.M.} &= \int^{BW} \frac{I_j(f)\,t_{ij}(f)}{T_i(f)}\, df \\ &= \frac{I_j(f')\,t_{ij}(f')}{T_i(f')}\,BW \end{aligned} \tag{3}$$

where f' is some frequency within the BW and the integral is approximated in the mean.

An "integrated current margin" (I.C.M.) is obtained by integrating the current margin density over the full common frequency range of the emitter and receptor according to the following:

$$\text{I.C.M.} = \int_{f_{lo}}^{f_{hi}} \frac{I_j(f)\,t_{ij}(f)}{T_i(f)}\, df \tag{4}$$

Equation (3) and (4) can be used to obtain both narrowband and broadband point and integrated current margins, as is currently done for average power in the IEMCAP. The two forms of P.C.M. could be used in a routine for generation of narrowband and broadband emission specifications. Subsequently, a "total point current margin" could be calculated for use in receptor spectrum adjustment for threshold vulnerable receptors.

Finally, a "total integrated current margin" can be calculated reflecting all narrowband and broadband emission spectra and the adjusted receptor spectrum. This total integrated margin would be the sum of the adjusted narrowband and broadband integrated margins over all emitters coupling to the receptor in analogy with the present average power approach.